MOTION PARALLAX AND THE PERCEPTION OF THREE-DIMENSIONAL SURFACES

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A Thesis Submitted for the Degree of PhD
at the
University of St Andrews

1983

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A thesis submitted for the degree of Doctor of Philosophy,

University of St. Andrews, January 1983.

Declaration

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Acknowledgements

The research reported in this thesis owes much to the inspiration and guidance of my supervisor, Dr. Brian J. Rogers, and, in some cases, as indicated, the research was carried out in collaboration with him. I am grateful for his infectious enthusiasm for visual perception and for the support and encouragement he has given me throughout the last few years. The initial work on motion parallax, reported in chapter 3, was started when I was an undergraduate. I was supported by a postgraduate scholarship from the University of St. Andrews while carrying out the majority of the research. Thanks are also due to the observers who took part in the experiments, often over long periods, and to my loving friends who gave their care and sympathy through all the traumas.

Motion Parallax and the Perception of Three-dimensional Surfaces

ABSTRACT

This thesis presents an empirical analysis of the depth cue of motion parallax. The history of research in this area is described and some recent computational models are outlined which show that parallax information can theoretically provide accurate information about the depth structure of the environment. In contrast to previous empirical work, which failed to demonstrate that motion parallax could be used effectively, the experiments reported in this thesis show that it can be an accurate source of information about depth structure. The characteristics of the processing underlying the use of motion parallax were investigated. Sensitivity to depth surfaces specified by relative motion was high, and it varied as a function of the spatial rate of change of depth. Moreover, the sensitivity function was similar to that measured for stereoscopic depth surfaces. The finding of close similarities between motion parallax and stereoscopic depth was a major theme of the thesis. Strong negative aftereffects followed prolonged viewing of depth surfaces specified by either cue and, in addition, large simultaneous contrast effects were also found. Here, the perceived depth of one area was affected by the depth of the surrounding area. These findings suggest that depth processing from both parallax and stereopsis involves extensive spatial interactions. A model of depth processing was suggested where the basic mechanisms had extended receptive fields which extracted changes in depth, specified either by relative motion or disparity, across local areas. The presence of anisotropies in the perception of depth surfaces showed that there was a differential sensitivity to particular local patterns of relative motion or disparity, which might be due to an asymmetric organisation within depth receptive fields. Finally, the motion parallax and stereoscopic depth processing systems were found to interact, indicating that information from the two sources might come together at some stage. Overall, the empirical findings emphasised the importance of extracting information about the local structure of depth surfaces rather than the depths of individual points.

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Chapter 1 General Theoretical Background

The importance of vision to an organism lies in its ability to provide information about present and future states of the remote environment, so that the consequences of action within that environment can be determined. In general, visually guided action and behaviour are carried out in an environment surrounding and extending away from the organism and this environment consists of surfaces and objects in a particular layout. The question of how the environmental layout is perceived has been the focus of philosophical debate and psychological research for centuries, and traditionally constitutes the topic of visual space perception.

Historically, the initial problem in this area was to understand how external spatial relations were coded in the retinal image. During the 15th and 16th centuries, after the nature of the image and the optics of projection had been worked out, a problem immediately became apparent. The following quote shows how Berkeley, the empiricist philosopher, characterised the basic problem of distance perception.

> "It is, I think, agreed by all, that distance of itself, and immediately, cannot be seen. For distance being a line directed end-wise to the eye, it projects to only one point in the fund of the eye. Which point remains invariably the same, whether the distance be longer or shorter."
>
> (Berkeley, 1709)

This dilemma of how we come to perceive an extended three-dimensional environment from a two-dimensional retinal image, has been the focus of a long debate between nativist and empiricist schools of thought, which has continued to the present day. The former school defended the view that the idea of visual space is innately present within an organism, while the alternative view held that the perception of distance depends, in Berkeley's words, upon "an act of judgement grounded on experience (rather) than on sense".

The more recent discipline of experimental psychology, because of its foundations in empiricist philosophy, has in the main seen the perceptual process as one of making judgements about the nature of the external world on the basis of experience. This viewpoint reached its most explicit form in Helmholtz's notion of "unconscious inference" (Helmholtz, 1925) and can be seen today in the work of Gregory (1970, 1980), where perceptions are considered to be analogous to hypotheses about the nature of the external world. Within this traditional viewpoint, the sensory data provided by the retinal image was seen to provide "criteria" by which perceptual judgements could be made. Since the retinal image contained no direct information about distance, the "primary" sensory data on which judgements about distance could be made, were thought to come from the convergent and accommodative responses of the eyes. "Secondary" judgemental criteria were also available through the interpretation of superposition, perspective and shadow, within the image. An observer learnt to make estimations of distance, on the basis of these criteria, through experience with the visual and tactile environment.

In line with this empiricist approach, research into the perception of depth and distance has historically been concerned with enumerating and analysing the various depth criteria or cues. As briefly mentioned, the artistic techniques which had been developed to represent depth in painting, and had been described in detail by

Leonardo da Vinci, were assigned the status of secondary depth cues. These included superposition, size and perspective, light and shade, aerial perspective and height in the visual field. The primary depth cues suggested by Berkeley had been convergence and accommodation, and, in the 19th century, a third primary cue was acknowledged, that of binocular stereopsis, or binocular parallax. This depth cue is based on the retinal disparities, or differences, between the images to the two eyes. That there was a difference between the two images had been noted since ancient times, by Euclid, Galen and da Vinci, among others, but the fact of binocular parallax and the presence of disparate images was seen as a problem for the visual system, rather than a potential source of depth information. It was believed that disparity should cause a "doubling" or a "confusion" in perception, and much effort was exerted to try and explain the apparent singleness of vision according to the theory of corresponding points (Brewster, 1844; Hering, 1942).

The connection between retinal disparity and the perception of depth was not fully grasped until Wheatstone demonstrated the compelling sensation of depth and distance produced by viewing disparate images using a stereoscope (Wheatstone, 1838; 1852). The development of the stereoscope led to an increased understanding of the principles by which it worked, and demonstrated the vivid effectiveness of stereopsis as a cue to depth. Viewed stereoscopically, figures and scenes stood out clearly in three dimensions and the amount and direction of the perceived depth was always predictable from the nature of the disparities between the two images. This powerful demonstration effectively set the scene for the next 150 years of research into the perception of depth. Stereopsis came to be seen as, by far, the most important source of depth information and it has been the focus of intense research up to the present day. This has meant that other sources of depth information have been largely ignored and there has been little theoretical or empirical analysis of their characteristics.

One of the other important but relatively neglected sources of depth information is that of motion parallax. Motion parallax was added to the list of depth cues by Helmholtz in the middle of the 19th century, and depends on the different perspective views of the world which are perceived from different viewing positions. As an observer moves laterally from one position to another the retinal image undergoes transformation and there is relative movement between the images of objects at different distances. The amount of relative movement is lawfully related to the distance of the objects and is, therefore, a potential source of depth information. The depth cue of motion parallax does not seem to have been explicitly mentioned in earlier optical texts, although Helmholtz discusses it as an accepted source of depth information. One probable reason for this omission is that parallax cannot be used to represent depth in pictures. It is also likely that the coming of fast locomotion drew attention to the relative movement between objects at different distances which accompanies motion of the observer and in fact Dove (1847) apparently mentioned the phenomenon after noticing it on a train journey.

The account of depth perception offered in many modern text books is still based on an outline of the traditional depth cues described by Helmholtz (see for example, Kaufman, 1974; Rock, 1975). However, although stereopsis is still considered to be the depth cue of major importance, an increasing emphasis has recently been placed on the so-called "kinetic" cues to depth which include and go beyond the traditional cue of motion parallax (eg. Haber and Hershenson, 1973). This change in emphasis reflects the growing influence of the theoretical and empirical work of JJ Gibson (1950; 1966; 1979). Gibson's approach offers a radically different view of perception to that of modern empiricism. Indeed his theories can be seen as arising from the nativist and Gestalt schools and, therefore, often directly conflict with empiricist assumptions. It is evident from a recent paper that the old empiricist-nativist debate is still alive today, albeit in a new form, and the vehemence of the members of each camp, seems to have lost little of its original force (see Ullman, 1980). However, Gibson has gone far beyond a traditional nativist position in his theoretical analysis of the nature and function of the perceptual process. Gibson sees perception, not as a making of inferences about the nature of the external world on the basis of sensory data and experience, but as a "process" whereby an animal actively seeks and "picks up" information about what the environment offers for action. Perception is a process of direct contact between the animal and the environment, and environmental opportunities are directly apprehended by the animal without being mediated by sensory impressions, inferences or internal representations. Gibson argues that regarding perception in this way necessitates a radical reappraisal of the nature of the visual information available to an observer, the processes involved in the "pick-up" of this information and the relationship between vision and action.

The main emphasis of Gibson's early work, and the part which has had the most influence on perceptual research in general, was to point out that the visual information available to a perceiver is very rich and is not limited to that present in a brief, static, retinal image.

When a perceiver moves in the environment, the "ambient optic array" undergoes certain lawful transformations which are informative about the three-dimensional structure of that environment. This changing optic array which accompanies movement of the perceiver, was called by Gibson, "motion perspective", and it incorporates and extends the traditional definition of motion parallax. Parallax traditionally refers to the motion between the images of isolated points at different distances, when the observer moves perpendicular to the line of sight, rather than to the transformation of the whole array which accompanies arbitrary observer motion. The perspective transformations of the array are a rich source of visual information and provide two different types of environmental information. The nature of the changing perspective provides perceptual information about the perceiver's own movement in the environment, and, at the same time, the perspective transformations themselves reveal the underlying invariant structure of the environment, by providing different perspective views of the persistent layout of surfaces and structure of objects. Gibson expresses this point by saying that, for optic flow, "the more it changes, the more it is revealed as the same thing".

In general, the impact of Gibsons approach has been to emphasise the information available in a changing optic array. Over the last twenty years, preliminary theoretical research has looked at how an organism could use this information to determine the structure of objects and the parameters of egomotion (Gibson et al., 1955; Lee, 1974), while empirical studies have investigated whether a human perceiver can actually use the information available (Wallach and O'Connell, 1953; Gibson et al., 1959; Johansson, 1973; Braunstein, 1976; Lee, 1980). More recently, several studies have attempted to precisely analyse the exact nature of the information available in optic flow, and to mathematically demonstrate the possible computations that could be carried out (Nakayama and Loomis, 1974; Koenderink and van Doorn, 1975; Longuet-Higgins and Prazdny, 1980). These last studies show the influence of a modern trend in visual research, the computational approach to vision, which has been heavily influenced by concepts from computational science and artificial intelligence.

The computational approach sees the goal of perception as the construction of a three-dimensional representation of the world from a two-dimensional intensity array. Rather than feature extraction and inferential procedures acting on the retinal image, the intensity array is transformed using computational procedures which act under certain predetermined constraints. This approach is, therefore, somewhere between a traditional empiricist and a Gibsonian approach since, although the use of inferential procedures and past experience is rejected, and the information about 3D form is acknowledged as present in the input, information about the third dimension is still, as it were, hidden and needs to be revealed by computational procedures rather than being directly perceived. In some computational models there is also the possibility of input from higher level cognitive processing. It has been suggested that such input may be necessary to explain some high-level visual illusions, for example those involving ambiguous figures, which seem to depend on cognitive information (Gregory, 1980).

The main thrust of the computational approach has been to emphasise the need to clearly specify the computational nature of the task facing the visual system, to make this task formally explicit and to produce a working algorithm to carry out the computation (Marr, 1980). The fruitfulness of considering visual perception in this way, has perhaps been most clearly demonstrated in the development of computational models of stereopsis. Several such models have now been developed and they have helped to clarify the problems inherent in extracting disparity information. They have also demonstrated the need to use environmental constraints on the computation, for example, the need to assume that surfaces will, on the whole, be smooth (Marr and Poggio, 1979; Mayhew and Frisby, 1980).

Following the success of these models of stereopsis, Ullman (1979) has attempted to devise an analogous computational model for extracting depth from motion. However, his analysis has relied heavily on the stereoscopic models, which has led to an overemphasis of the problem of matching corresponding points between successive images and a failure to adequately consider the overall nature of the proximal change. An adequate computational model of depth from motion has not yet been developed, although the computational nature of the task has been outlined in some detail in the studies mentioned above. One of the major criticisms of computational models of depth perception in general, is that the assumed end product of the computation may not be appropriate for the task at hand. The goal of the present models has been to produce a "depth map" of the image, where each visual direction is given an associated depth value. However, in order to perceive three-dimensional surfaces and objects it is necessary for the visual system to extract information about change of depth over space. The computation of depth change may follow the computation of a depth map or, alternatively, the two processes might be interdependent. Moreover, it might not be necessary to know the depth of any particular point in the image in order to perceive a depth surface. Present computational models may, therefore, be misguided in their underlying aims.

At the same time as the increasing influence of the computational approach to depth perception, the later work of Gibson and the more recent development of his approach by Shaw, Turvey, and others has acted to apply recent theoretical developments in biological sciences to visual perception (Shaw and Turvey, 1981). This work stresses the mutuality between the perceiving animal and it's environment, in other words the mutual tailoring of perception and action to one another. In practical terms, this approach has looked at visually guided activity in the environment, and analysed how the visual information and the movement of the animal interact to allow successful execution of activity. Research in this area has, therefore, been mainly concerned with using visual information about a perceiver's own activity while carrying out a task, rather than using the information about three-dimensional structure which is also available from the optic flow (Lee, 1980). This manner of looking at perception is only in its infancy and it seems likely to provide insights into the nature of perception, as a whole, and the pick-up of information about three-dimensional structure, in particular, over the next decade.

In summary, it seems that after a long period of neglect, dynamic sources of depth information are becoming increasingly important for the understanding of depth processing and visual perception in general. Further advances in this area are likely to incorporate the insights of both computational and Gibsonian approaches to perception, and it is important that there is a firm empirical base to guide and evaluate theoretical development and to suggest new directions. The small amount of previous research that has been carried out in this area has produced ambiguous results due to the varying theoretical backgrounds and techniques used in the experiments. This has been particularly true of research concerned with determining whether human observers can use motion perspective transformations to gain information about three-dimensional structure (Gibson and Carel, 1952; Braunstein, 1968; Eriksson, 1973; Johansson, 1973). It has proved difficult to find an experimental technique which allows the use of complex optical transformations as well as isolating motion as the only available source of depth information.

The research reported in this thesis, provides a detailed initial exploration of one type of motion perspective, that of motion parallax. It has been carried out using a new technique which does allow parallax to be studied in isolation from other sources of depth information. Motion parallax, here, refers to the motion perspective which accompanies motion perpendicular to the line of sight. Motion in this direction potentially provides good information about the three-dimensional structure of the environment, and such information is the focus of the present thesis. (Motion in the same direction as the line of sight, mainly provides information about the path and direction of egomotion.) The aim of the research has been to provide an initial empirical characterisation of motion parallax as an independent source of depth information, and to determine some of the parameters of the motion parallax processing system used by human observers. A further consideration behind this research, has been to compare the characteristics of the motion parallax system with those of the stereoscopic depth system, which has already been extensively studied, so that the similarities and differences between the two systems can elucidate the nature of depth processing in general.

CHAPTER 2 Previous Research on Motion Parallax as a Source of Information about Depth and Distance

2.1 Traditional studies of motion parallax.

The initial analysis of motion parallax as a source of information for depth and distance was provided by Helmholtz towards the end of the last century. Since that time motion parallax has been acknowledged as an important source of depth information although it has received relatively little empirical investigation. Helmholtz's description is still worth reading today and forms the basis for the description of motion parallax in many modern textbooks (Helmholtz, 1925).

> "In walking along, the objects that are at rest by the wayside stay behind us; that is, they appear to glide past us in our field of view in the opposite direction to that in which we are advancing. More distant objects do the same way, only more slowly, ... Evidently, under these circumstances, the apparent angular velocities of objects in the field of view will be inversely proportional to their real distances away; and consequently, safe conclusions can be drawn as to the real distance of the body from its apparent angular velocity. Moreover, in this case there is a relative displacement of objects at different distances with respect to each other. Those that are farther off as compared with those that are nearer seem to be advancing with the observer, whereas those that are nearer appear to be coming toward him."

Helmholtz refers to motion parallax as a potential source of information about the absolute distance of objects from the observer, as well as about the relative distances between objects. The former can be determined from the angular velocity of the image of the object, while the latter is related to the differential velocity between the images of different objects. Helmholtz also emphasised the potential importance of motion parallax as a source of depth information and pointed out its relationship to stereopsis.

> "More importantly, however, for the estimation of distances, and more accurate than all the incidental aids mentioned [pictorial depth cues], is the comparison of the perspective views of the same object as seen from different points. Practically, there are two ways in which this can be done, either in monocular vision by moving the head and body, or in binocular vision by means of the two different images of the same object at the same time in the two eyes."

Finally, Helmholtz suggested that motion parallax provided the same phenomenal impression of depth as stereopsis.

> "Suppose, for instance, that a person is standing still in a thick woods, where it is impossible for him to distinguish, except vaguely and roughly, in the mass of foliage and branches all around him what belongs to one tree and what to another, ... the moment he begins to move forward, everything disentangles itself, and immediately he gets an apperception of the material contents of the woods and their relations to each other in space, just as if he were looking at a good stereoscopic view of it."

A more detailed geometrical analysis of motion parallax based on that offered by Helmholtz, has been presented by Graham (1965). Within this traditional definition, motion parallax rests on the ability to detect the differential angular velocity between the lines of sight to two objects. The geometry behind this type of analysis is shown in Figure 2.1. From this figure it can be seen that motion parallax can act as a relative depth cue, since the differential angular velocity is a linear function of the distance between two objects, and can also act as an absolute cue, if the extent of lateral movement and the direction of gaze can be determined. The relation to stereopsis can be appreciated by considering two viewing positions which are separated by a distance equivalent to the interocular distance. In this case the

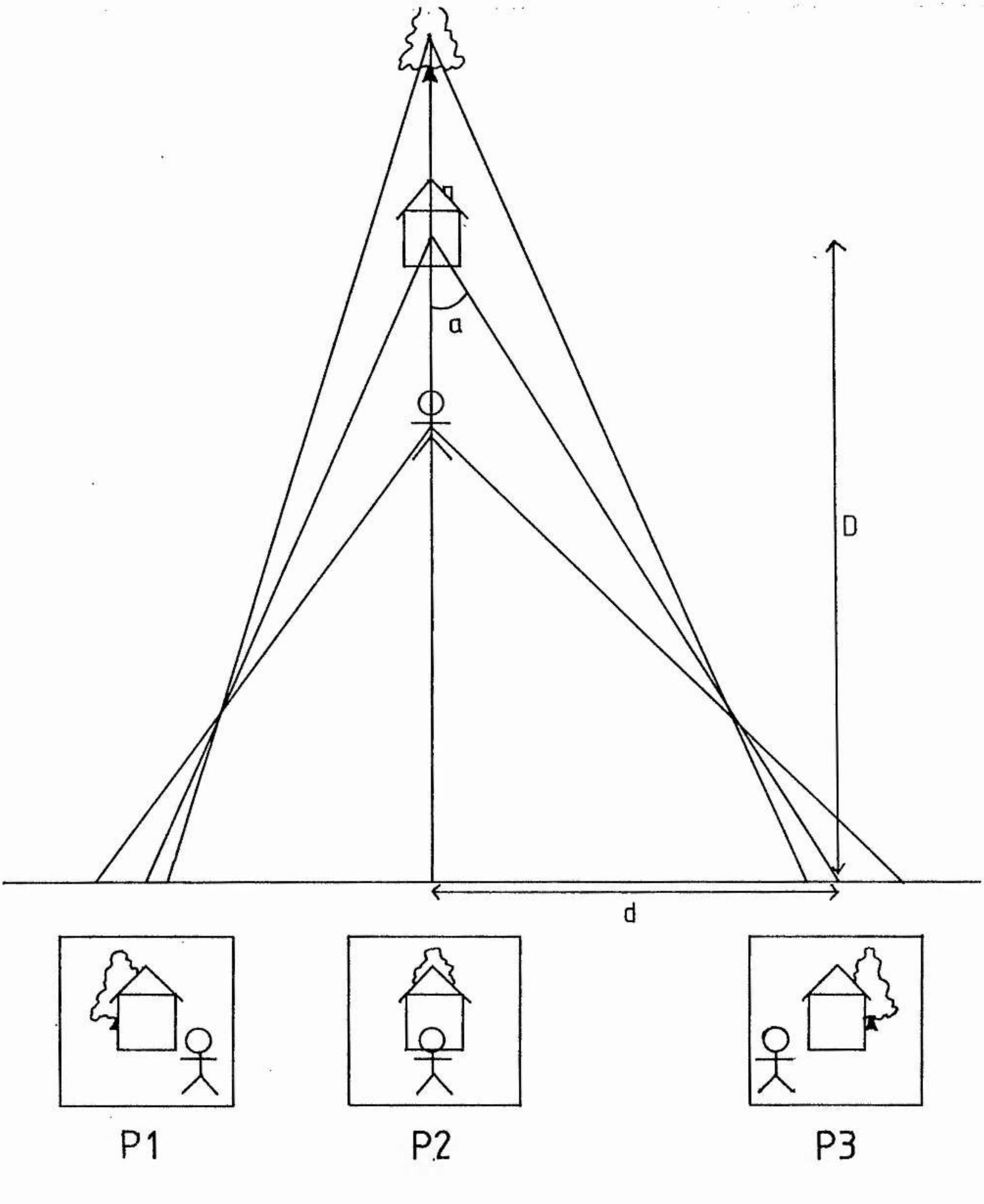


Figure 2.1.

As an observer moves from P1 through P2 to P3 the relative positions of three objects change and there is a differential angular velocity between the lines of sight to the different objects. This differential velocity is a linear function of the relative distance between objects so that, for example, the relative motion of the tree with respect to the person is greater than the relative motion between the house and the person. If P1 and P2 are separated by the interocular distance then the difference in relative position of the three objects at P1 and P2 corresponds to the disparities which would be present if the scene was viewed binocularly from the midpoint of P1 and P2.
Absolute distance can be computed if the angle of sight and distance travelled are known, since $D=d/\tan a$.

information gained by comparing the two views binocularly can also be obtained monocularly by moving from one position to the other.

Following this type of geometric analysis, motion parallax became accepted as an important potential source of depth information. However, only intermittent attempts were made to empirically demonstrate that motion parallax could actually be used as a veridical cue for depth, by human observers. The earliest of these attempts seems to have been made by Bourdon (1902) who showed that the spatial order (relative distance) of two lights in a corridor could only be determined monocularly if subjects moved their heads. This was true for distances of two to twenty metres. In an attempt to discover how much head movement was necessary, Cords (1913) reported that the depth perceived by motion parallax was constant when the extent of head movement was 3cms or more, and no depth was perceived when it was less than 1cm. The next major study was that of Tschermak-Seysenegg (1939), who made the first threshold measurements for motion parallax. She determined that the threshold depth difference which was required to perceive two wires as being at different depths, was 0.8mm for monocular viewing with head movement at a distance of 21cms. This compared with a threshold depth difference for binocular viewing of 0.5mm.

The geometric analysis given in Figure 2.1 was described for a moving observer looking at stationary objects. A symmetrical analysis can be made for the case of a stationary observer viewing objects translating across the line of sight. This situation, which will be called a passive parallax situation, is easier to set up and control in a laboratory situation and has been used in the two most extensive studies of motion parallax thresholds, those of Graham et al.(1948) and Zeegers (1948). Both these studies were concerned with the effect of certain parameters on the thresholds for detecting depth differences. In particular, the extent and velocity of lateral movement were investigated since these parameters determine the overall displacement, and are therefore likely to affect thresholds. Both studies used a task where two thin needles, one above the other, were moved laterally across the observers line of sight. The observers task was to adjust the distance of one needle until both needles appeared to lie in the same depth plane. The threshold angular velocity was then computed from the deviation of the errors in the depth settings. Graham et al. (1948) found that the threshold differential angular velocity could be as low as 30 arc seconds per second. Thresholds increased with overall rate of stimulus movement up to a maximum of 2 arc minutes per second for stimulus movements of 17 degrees per second and above. Thresholds were lowest when the movement of the needles was in a horizontal direction and increased by just under a factor of two for vertical movement, confirming an anisotropy reported in Tschermak's study. Zeegers (1948) confirmed that increases in stimulus velocity increased differential velocity thresholds and also investigated the effect of varying the overall excursion. He demonstrated that, for a given overall velocity, motion parallax thresholds were determined by the maximum visual angle separating the comparison and test stimulus during their lateral excursion.

These threshold measurements show that the visual system has a high acuity for detecting differential angular velocity. It is not clear, however, how this relates to the perception of depth per se. Graham, for example, reports that observers perceived either depth separation or differential velocity between the two objects, or even just the offset or misalignment of the two needles at different parts of the motion path. In order to demonstrate the effectiveness of motion parallax as a source of depth information it is necessary to do more than demonstrate that it is possible to pick up small differences in angular velocity or vernier alignment. A way of overcoming this difficulty is to look at tasks which use measurements taken above threshold. Experiments that have attempted to use this type of task have, however, only provided equivocal evidence for the effectiveness of motion parallax.

Most tasks of this kind have involved distance estimation or distance matching. Gibson, Gibson, Smith and Flock (1959) carried out one such experiment as part of a larger study to be described later. In a passive motion parallax situation, stationary observers were shown shadows of two spots at different distances which moved laterally across the line of sight. Because of the depth difference there was a differential velocity between the shadows of the two objects but accommodative cues were eliminated. Gibson et al. found that although the differential velocity caused the two spots to appear to be at different distances, the extent of the depth separation between the objects, their absolute distance from the observer, and even their relative order in depth was not consistently perceived.

More recently, in a series of experiments which looked at the effectiveness of motion parallax in the presence of other depth cues, Eriksson (1972a, 1972b, 1973) found similar results. Although head movement allowed the depth separation of two objects to be perceived, the extent of the separation was underestimated and the direction of the depth difference was ambiguous. The order of the two objects was determined by the other cues present, such as, height in the visual field, rather than by the direction of the velocity difference. Other experiments by Gogel and Tietz (1973, 1974) have shown that the differential velocity provided by head motion is insufficient to correct a false depth impression produced by other cues such as perspective. A developmental study by Degelman and Rosinski (1979), again found that absolute and relative depths were underestimated, while a study by Redding et al. (1967) failed to find any improvement in a distance matching task due to head movement, unless the degree of body sway was greater than 46cms., -a much larger amount than that used in most other studies.

On the other hand, there have been studies which have indicated that motion parallax can be an effective cue for depth. In particular, Johansson (1973) found that lateral head motion allowed very accurate estimation of the absolute distance to an array of four lights, and Ferris (1972) found that distance judgements using motion parallax improved dramatically with training. A more recent, detailed study by Hell (1978) used a different means of measuring the effectiveness of motion parallax. In a size matching task, ths subject was required to set the width of the farther of two objects to match the width of the nearer. The amount of size constancy shown was taken as a measure of effectiveness, for conditions using different extents and velocities of head movement. The amount of constancy reached an asymptote of around 50% when the amplitude and velocity of head motion exceeded a certain value which, when computed using threshold values found in previous studies, was about 10 times threshold. In the conditions of this experiment this was equivalent to a head movement of 6cms. at a velocity of 6cms. per sec. In the same study, Hell showed that a succession of disparate images from different positions was not sufficient to provide motion parallax information, which depended on the presence of relative velocity. However, the procedure in this condition was rather awkward for the subject, so this result must remain tentative.

Using the same technique, Hell and Freeman (1977) found that the effectiveness of motion parallax decreased as the angular separation between the test and comparison object increased. This appears to be related to the increase in differential angular velocity threshold (Zeegers, 1948), and the increase in thresholds for detecting relative motion between two spots (Brown, 1961; Harvey and Michon, 1974), which occurs with increasing angular separation. In this study the effectiveness of parallax was also influenced by the nature of the background and its velocity relative to the objects. Finally, a rather ingenious way of measuring the effectiveness of parallax was used by Wallach and O'Leary (1979). They looked at whether observers would adapt to wearing prisms which altered the relationship between the accommodative response of the eye and the distance of focussed objects. Adaptation was found to occur when motion parallax was the only veridical source of depth information which could allow the visual system to recalibrate the relationship. They took this to indicate that parallax had been acting as an effective cue.

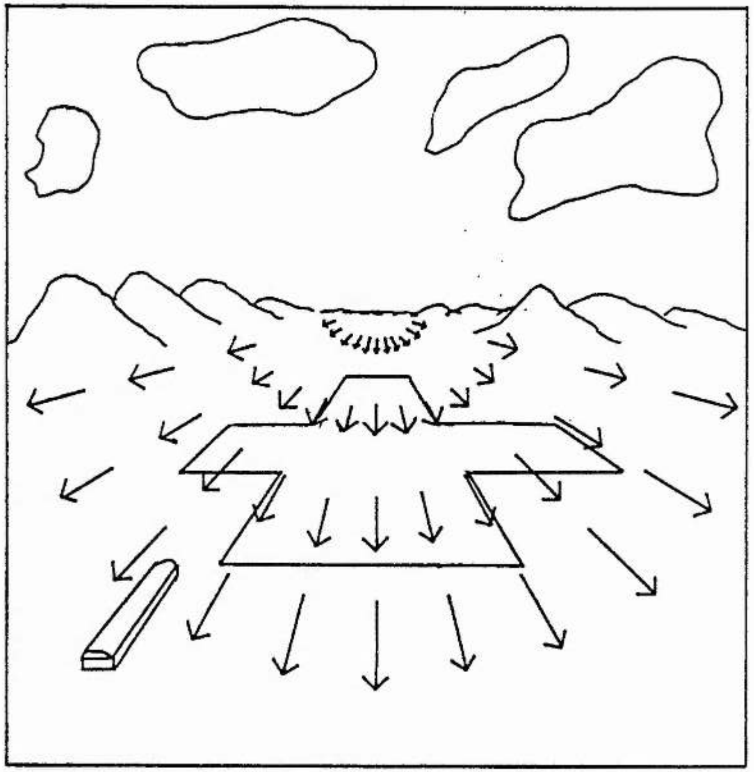
The discrepancies between the results from these different experiments, probably reflect the wide variety of techniques and procedures used. One variable which might be important is whether parallax was investigated in a task using active head movement or whether passive parallax was studied. In the studies cited, active head movement parallax seems to provide more effective information, perhaps due to the extra information that is available from the motor and vestibular systems in this case. Experiments have also varied to the extent that other cues, either in conflict or in agreement with parallax, have been present in the stimulus situation. Finally, another important factor seems to be the presence or absence of a background to provide a reference for the stimulus objects. This reflects an important common feature of the experiments described so far, which have all involved differential angular velocities between just a couple of points or lines. Although this is in line with the traditional geometrical analysis of parallax, it may be that this situation is not sufficiently complex to allow motion parallax to be utilised effectively. In everyday life, after all, the visual world is filled with surfaces and objects at different distances and as we move there is a whole flow of relative motion between the images of different parts of the field, rather than merely a difference in velocity betweem two isolated points. Such an argument formed the basis of an extended theoretical analysis of motion parallax which was developed by J.J. Gibson in the 1950's. His work initiated a series of experiments to determine whether a flow of relative velocities would be a more effective source of information about depth separations and the three-dimensional shape of objects.

2.2 The effectiveness of velocity gradients.

In "The Perception of the Visual World" (1950), Gibson described the way in which the proximal stimulus changes with movement of an observer through an environment. In general, movement causes a whole pattern of flow which Gibson has called motion perspective. An intuitive grasp of the motion perspective accompanying locomotion can be appreciated from Figure 2.2. Gibson, Olum and Rosenblatt (1955) gave a mathematical analysis of the nature of this perspective or optic flow and showed that it contains information which theoretically allows the computation of the depth structure of the environment and the direction of movement of the observer. This analysis included and went beyond, the traditional geometric analysis of motion parallax outlined earlier. Gibson gives the following reanalysis of the Helmholtzian definition of motion parallax.

> "Apparent angular velocity is proportional to distance, true enough, but it is also a function of O's line of locomotion. As angular deviation from this line decreases apparent motion also decreases and finally vanishes. In other words, the apparent velocities of objects scattered in the visual field seem to be complicated by the fact that they "carry information" not only about the distances of objects but also about the direction in which O himself is moving."

Gibson's analysis has provided new insight into the depth cue of motion parallax and has generated a lot of research with particular emphasis on the optic flow which accompanies approach of an observer to an obstacle. His analysis has been extended and more rigorously defined by several authors in the last decade and a model based on such an analysis will be outlined below. The immediate impact of Gibson's work was to generate a series of experiments to show that a flow or gradient of velocities was an effective source of depth information, and to compare this type of stimulus with the two velocity situation, used in the experiments described above.



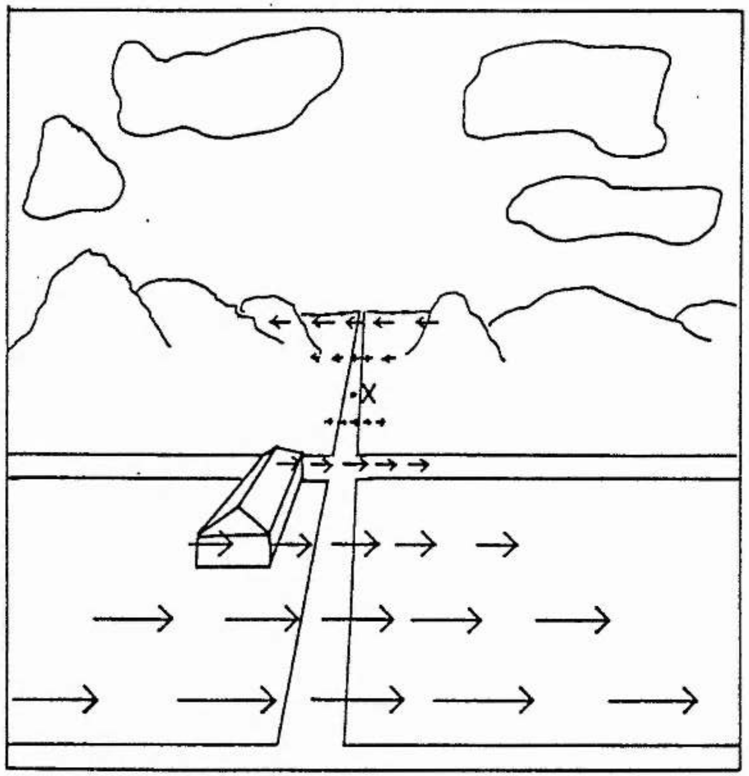
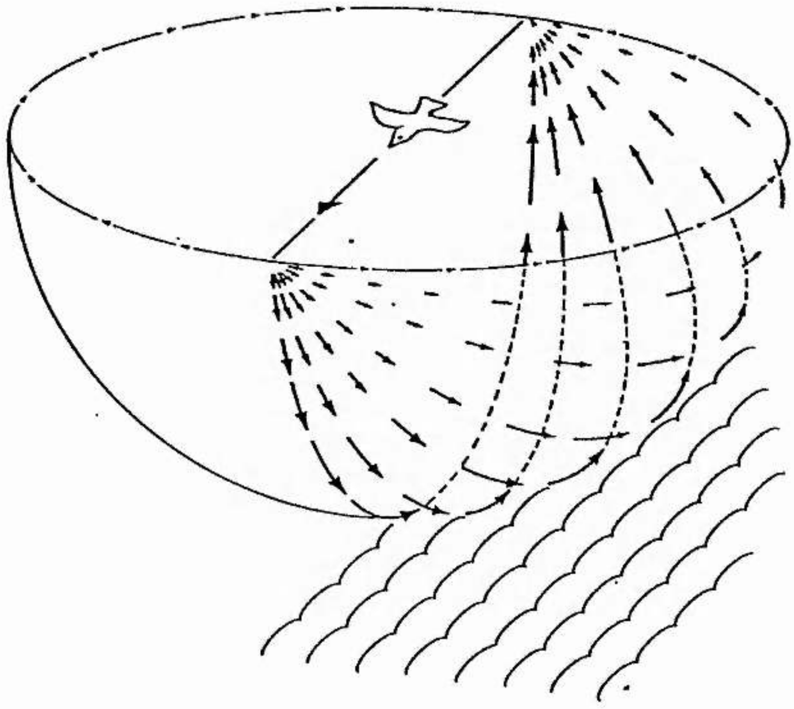


Figure 2.2.

(a) The optic flow ahead for a pilot flying parallel to the ground.

(b) The optic flow for a pilot flying laterally while looking at X.



(c) The general pattern of optic flow around an observer.

In an early attempt, Gibson and Carel (1952) presented observers with a moving bank of luminous dots, containing a gradient of velocities, and found that, contrary to their prediction, observers failed to perceive a surface sloping in depth. However, in a detailed study, Gibson, Gibson, Smith and Flock (1959) obtained a more positive result. They used a shadow-caster technique to project shadows of differentially moving textured planes. The shadow projection of two transparent random dot planes at different distances appeared as one surface when they were stationary, but gave a consistent impression of two surfaces separated in depth when a differential velocity was introduced between the two planes. In addition, a shadow pattern containing a gradient of velocities from the top to the bottom of the pattern, was perceived as a slanting surface receding in depth. However, judgements of absolute distance were inconsistent in all cases and the extent of depth separation in the two plane case was underestimated. Following this study, Smith and Smith (1963) used a combination of two velocity and continuous velocity gradients. They found that although this stimulus yielded a veridical perception of the order of two surfaces in depth, the extent of the separation was underestimated and the velocity gradient failed to give a consistent impression of a sloping surface. On the other hand, Flock (1964) found that velocity gradients were sufficient to specify sloping surfaces, and, moreover, that gradients representing surfaces which sloped at an angle of between 40 and -40 degs. from the vertical, were correctly ranked with respect to the degree of slope. In addition, the judged slope was very close to the physical slope. Park (1964) also found that velocity gradients gave rise to perceived slant but he again found that the degree of slant was underestimated.

In summary, these experiments on the perception of depth from velocity gradients only gave slightly better evidence for the effectiveness of motion parallax information than the two velocity case considered earlier. In reviewing these experiments, Epstein and Park (1964) concluded that: "These experiments failed to provide evidence that motion parallax in isolation is adequate to specify depth, slant or the relative order of surfaces in depth." Moreover, in a more recent review of the literature Gogel (1977) concluded that: "Although relative motion parallax is often assumed to be one of the effective exocentric cues, the evidence seems to be equivocal."

Before looking at possible reasons for these equivocal results it is interesting to consider Gogel's interpretation of these experiments on motion parallax. He maintains that the perception of a differential velocity between two objects is sufficient to indicate that they are at different depths but is insufficient to provide a phenomenal impression of depth between the objects. He points out that if an apparent motion is actually perceived during movement in the environment (as experienced on a train, for example) then this, in effect, indicates a failure of motion parallax to act as a veridical depth cue. He suggests that, in general, the distances actually perceived in any situation are determined by the other depth cues present, and the proximal relative motion is interpreted in accordance with these perceived distances. Hence, if these distances are incorrectly perceived then relative motion of objects and surfaces will be perceived which is concomitant with the motion of the observer. An example of this occurs when an observer moves while viewing a hollow mask which is incorrectly perceived as a normal face (Gregory, 1970). The face appears to rotate with the observers movement due to the misperceived depth relationships within the mask. In an elegant series of experiments Gogel and Tietz (1973, 1974, 1980) have been able to use the apparent motion concomitant with head motion as a measure of the perceived distance of objects when their distance was specified by other depth cues such as perspective. However, in these experiments parallax information was only provided by the relative motion between two isolated points and this may not have been an optimal situation for the effective use of parallax.

The discouraging nature of the experimental studies designed to demonstrate the effectiveness of motion parallax, seems to result from the lack of an adequate stimulus situation where motion parallax can act effectively as source of depth information. This conclusion is supported by the fact that very powerful depth effects can be produced by other kinds of perspective transformations. Study of these depth effects has led to a renewed interest in motion perspective as a whole, and to several theoretical developments in the area over recent years. On the empirical side, since their development in the 1960's, computer techniques for producing moving stimulus patterns have proved to be a useful experimental tool for controlling and manipulating the various parameters involved in different types of motion transformations. Computer techniques have, however, mainly been used to investigate the motion transformations which accompany rotation of a 3D object, although a few studies have also included motion parallax transformations, that is, transformations accompanying object motion perpendicular to the line of sight.

2.3 The Kinetic Depth Effect.

In 1953 Wallach and O'Connell carried out the first detailed study of an interesting depth effect which had been noted earlier by Miles (1931) and Metzger (1934). These authors had noticed that the two-dimensional shadows or silhouettes of some three-dimensional objects, such as fans or windmills, often appeared to be as three-dimensional as the objects themselves. To investigate this phenomena in more detail, Wallach and O'Connell used a shadow casting apparatus where a shadow of an intervening object was cast on a translucent screen by a point light source. When the object was stationary the two-dimensional shadow looked flat, however, when the object was rotated there was an immediate, striking impression of a solid three-dimensional rotating object. This perception of depth in a 2D transforming pattern was labelled the "Kinetic Depth Effect". It was noted by Wallach and O'Connell that the transforming shadow simulated the series of perspective transformations that would be perceived as an observer walked around a stationary object, ie; it simulated a kind of motion perspective. One interesting characteristic of the Kinetic Depth Effect (KDE) was that the internal depth relationships of the perceived object and its direction of rotation were not consistently perceived. The shadow was either seen as a 3D object with a particular front-back relationship rotating in one direction, or as a 3D object with the reversed front-back order rotating in the opposite direction, and these two possible interpretations would often alternate spontaneously. This perceptual ambiguity is, in fact, consistent with the geometry of the situation since the method used ensures that the shadow is projected approximately orthographically, that is, it approximates a parallel projection. A rotating 3D structure has the same orthographic projection as its mirror image, rotated by the same amount in an opposite direction, and so the ambiguity is inherent in the nature of the stimulus pattern (see Ullman, 1979).

As mentioned above, computer generated stimuli have been extensively used to study the KDE. Green (1961) was the first to develop this technique which allows arbitrary motions of groups of dots to be produced on a two-dimensional surface, so that the motion of actual objects is not required. To produce KDE stimuli, the changes in position of dots or lines placed within, or on the surface of, an imaginary object such as a sphere, are computed as the sphere undergoes hypothetical transformations. The two dimensional projection of the imaginary sphere is then computed at discrete intervals during the transformation, and a series of these projections is used to produce a transforming 2D pattern. This technique has been used extensively by Braunstein whose many experiments in the area have been summarised in his book "Depth Perception through Motion" (1976). He has looked at the perceived depth for transforming patterns which simulate the transformations occuring during rotation and translation of an object about the three axes of visual space. Concerning the KDE, Braunstein has looked at the conditions under which the correct depth order and direction of rotation is perceived and has shown that accuracy increases gradually as the projection point distance decreases so that the projection becomes polar rather than parallel (Braunstein and Payne, 1968). The use of polar projection introduces several perspective effects into the transforming pattern and these can be used to disambiguate the rotation direction. They include relative size and velocity differences between front and back surfaces, the location of minimal velocity points and the ratio of acceleration to displacement along a row of points. Both vertical and horizontal perspective effects have been shown to be effective in reducing rotation ambiguity (Braunstein and Payne, 1968; Hershberger and Starzec, 1974; Hershberger, Carpenter, Starzec and Laughlin, 1974). The initial experiments on the KDE, carried out by Wallach and O'Connell, had attempted to determine whether changes of motion in both a vertical and horizontal direction were necessary for the depth effect to be perceived. This hypothesis generated a lot of experimental research (White and Mueser, 1960; Johansson and Jansson, 1968; Braunstein, 1976) but it now seems that it is not necessary for the pattern to undergo change in two dimensions provided that other stimulus conditions, such as the number and separation of dots and the amount of relative movement between them, are appropriate (Braunstein, 1976). Other factors that have been shown to decrease the accuracy and stability of the KDE are a decrease in number of elements or views (Green, 1961; Braunstein, 1962) and an increasing presence of random noise (Petersik, 1979).

In an attempt to elucidate the crucial motion properties responsible for the perception of depth in the KDE, rather than simulating the transformations produced by real objects, Johansson and his colleagues have looked at patterns of dots with simpler movement parameters. Borjesson and von Hofsten (1972, 1973, 1977) used patterns containing only two or three dots, to look at the relationship between the type of proximal motion (common or relative, sinusoidal or linear) and the perception of rotatory and translatory motions in depth. They found that, concurrent, linear motions tended to favour the perception of translation while parallel, relative, sinusoidal motions favoured rotation percepts. Similar studies for lines (Johansson and Jansson,

1968) and polygons (Jansson and Johansson, 1973) have also been carried out. From these experiments, Johansson has developed a model of motion perception based on a perceptual vector analysis of the proximal stimulus. In his analysis, the motion of each point is broken down into a component of common motion which is shared with other dots and a remaining component of relative motion with respect to other dots. In order for depth to be perceived the relative motion components must be non-zero. An important feature of this analysis is that it is not solely the particular motion of a point which determines its perceived depth and motion but rather, the motion of any point has to be interpreted with respect to the whole pattern of motions occuring throughout the visual field. In other words a global analysis of the pattern of motions is necessary (Johansson 1975,1977). Another important aspect of this model is that, the visual system is considered to "assume" that the motion pattern which it is processing, arises from a projective transformation of a rigid three-dimensional object. Although previous studies had pointed out that in the KDE the visual system in some sense seems to prefer a three-dimensional interpretation of a transforming array (Wallach and O'Connell, 1953; Gibson and Gibson, 1957; Hay, 1966), Johansson actually built such a principle into his analysis. The model assumes that the visual system is primarily tuned to interpret motions as projective transformations and within this framework it "automatically abstracts a maximum of projective invariance in the transformation .... rigid motion is what is basically sought for" (Johansson, 1977; 1978). Once the interpretation which allows maximum projective invariance has been discovered, the residual motion is interpreted as motion of the rigid object or as a form change of parts of the object.

Similar models to that given by Johansson have also been developed by Hay (1966), who presents an algebraic model of the KDE, and by Restle (1979) who applies the coding theory developed by Leeuwenberg (1978) to the perception of depth from motion. In the latter analysis the perceptual code represents the relative and common motion components and a minimum solution is sought; an analogous process to the search for maximal projective invariance in Johansson's model.

A formal description of the amplitude, phase and temporal characteristics of the visual systems response to the Kinetic Depth Effect, has been outlined recently by Caelli (1979,1980,1981). From an extensive series of experiments involving the projections of rotating angled rods, spirals and dot cylinders, he has developed a network model for both the KDE and apparent motion. The model uses a filtering mechanism, the bandwidth of which coincides with the spatiotemporal limits of the psychophysical effects measured for human observers. According to the model the visual system initially extracts the geometric properties of small regions of the transforming pattern and interprets the projection values (perspective) of each region with respect to the observer. The process is time dependent and the three geometric parameters which determine the structure of the object, slope, curvature and torsion are determined in sequence, the latter two being determined only up to a sign. Caelli has shown that the rotation rate must be under 2Hz for all parameters to be successfully extracted. The assumptions of this model echo those given by Johansson. Caelli concludes "that the visual system has a priority for interpreting projected 2D images as central projections and that there is a tendency (consistency) to preserve the rigidity of the (rotating) reconstructed

3D object" (Caelli, 1980)

From a rather different approach a very elegant model of the extraction of depth from motion has been developed by Ullman (1979) and this model shares the ideas of local processing and rigidity preference found in Caelli's model. Working within the artificial intelligence paradigm, Ullman has produced a computational theory which has led to a working implementation of the depth extracting process. The model takes, as input, static views of the projection of dots on the surface of a three-dimensional object at different points during a motion transformation (usually a rotation of the object). Initially a "correspondence" process matches dots in successive images and, once a match has been obtained, a simple structure-from-motion theorem is applied to the image. The computation is carried out under a single constraining principle, which Ullman calls the "rigidity assumption", whereby, if a 2D set of transforming elements has a unique interpretation as a rigid body then it is interpreted as such. The structure-from-motion theorem derived by Ullman, can then be successfully applied, under the rigidity constraint, to any transforming pattern and will determine its underlying three-dimensional structure. The theorem states that "given three distinct views of four non-coplanar points in a rigid configuration, the structure and motion compatible with the three views are uniquely determined". Using this theorem, the structure is determined up to a reflection in the projection plane, because of the inherent ambiguity of the orthographic projection. For the more normal case of polar projections, Ullman has shown that the computation can be carried out locally, on small groups of four or more elements, by assuming orthographic projection over this area. Once the structure and motion of each area has been determined up to a sign, the overall structure can then be veridically computed by working out the overall axis of the projection.

The power of Ullman's analysis of the KDE lies in the fact that he has made the problem facing the visual system formally explicit and has proved that the three-dimensional strucure can feasibly be computed. Moreover, he has designed a particular algorithm which can implement the computation and produce the appropriate 3D strucure when given a transforming 2D projection of a rotating object. On the other hand, it can be seriously doubted that the solution adopted by the visual system is in any way similar to the computational solution offered by Ullman. It seems more likely that, rather than using static views, the visual system would make use of its ability to extract the derivatives of motion. Physiologically, the coding of velocity information seems to be of prime imnportance in the visual system and it seems likely that velocity information would be directly extracted as a basic processing parameter (Grusser and Grusser-Cornehls, 1973). Moreover, as discussed below, Ullman's particular model is not well suited for extracting depth from projections of translating, rather than rotating, objects. Finally, however, Ullman's algorithm does seem to produce performances which are similar to those shown by human observers. It predicts, for example, the presence of perceptual reversals, the number of dots needed to perceive the effect, and the greater difficulty of perceiving depth for plane surfaces. It is not yet clear whether it can also predict the detailed geometrical and filter characteristics of the KDE which have been empirically determined by Caelli. Whatever its ultimate explanatory value, Ullman's work provides an impressive analysis of how depth information could be perceived from transforming two-dimensional patterns.

2.4 Motion parallax transformations.

The large amount of research which has been carried out on the Kinetic Depth Effect has, in a few cases, led to similar experiments on transformations which provide information more similar to that provided by the traditional depth cue of motion parallax. Most notably, Braunstein has looked at the perception of depth in computer generated projections of objects translating across the observer's line of sight. He found, for example, that the two-dimensional projection of dots belonging to a translating cylinder elicited strong depth impressions (Braunstein, 1966) and also showed that, for slanted planes, a velocity gradient was much more effective in determining perceived depth than a texture gradient (Braunstein, 1968). In both cases, the front/back depth relationship of the perceived three-dimensional structure was sometimes ambiguous, even though polar projections were used in these experiments. Polar projections were used here because a parallel projection of a translating object does not contain differential velocities and is not perceived as three-dimensional (Braunstein, 1966).

More recently, Farber and McConkie (1979) looked at dot patterns containing gradients of velocities which approximately simulated two slanted planes meeting at a horizontal angle, which was either toward or away from the observer. They found that the observers were unable to report whether the two surfaces formed a concave or a convex angle and concluded that motion parallax was an ineffective source of depth information. However, the actual patterns used in this study, actually simulate the rather strange case of planes meeting at infinity. Moreover, the logic behind the experiment has been strongly criticised by Prazdny (1981).

In a more detailed and controlled study, Braunstein and Andersen (1981) have shown that high accuracy for relative depth judgements can be achieved using very similar velocity patterns. They found that overall dot speed increased the accuracy of depth judgements. They suggest that Farber and McConkie's situation was not optimal in terms of either the speed and duration of the stimuli or the fixation conditions and also because of the presence of conflicting indications of flatness in the display. Braunstein and Anderson also noted that, in their experiment, the perceived depth surface often appeared to rotate as well as, or instead of, translating. This perceived rotation occurred in two different situations. In the first, the order of relative depth was correctly perceived and a small perceived rotation accompanied the translation of the object. This effect appeared to be due to an underestimation of the extent of the internal depth within the object. In the other case, the depth order was incorrectly perceived and the surface appeared to undergo a large rotation in the opposite direction to the actual translation. Here, rotation was often accompanied by the perception of form change such that the surfaces appeared to distort as they moved. In this latter case the translating dots appeared to be due to an object rotating in depth, as in the KDE, and were not perceived as belonging to a translating object. In this respect, it seems that experimental conditions which emphasise the linear rather than sinusoidal velocities of the dots favour the correct perception of relative order and translation, since it is these velocities which specify that a translation rather than a rotation is occuring. Braunstein found that such conditions were large overall display velocities and a low ratio between the relative velocity of the fastest and slowest moving dots and the overall translation velocity. It seems very likely that some of the discrepancies among earlier studies, particularly with respect to judgements of relative depth order, were due to these temporal factors.

The perceptual effect of transformations accompanying translation of three-dimensional objects are very similar to those found in the KDE, and we can perhaps look for similar models for the two types of effect. Although Ullman's computational model of the extraction of depth from motion is a general model which should be applicable to any type of 2D transformation, it was primarily designed to handle the perspective transformations which accompany rotation of an object. In theory it can handle transformations which accompany an object's translation, in depth or along a line orthogonal to the line of sight, but in practice the polar-parallel structure from motion theorem would only work well in these cases for large textured objects undergoing large translations. This is because of the need to obtain three "distinct" views of the object, that is, with each view from a different plane. This would imply that depth is perceived more readily from rotation than translation transformations. It does seem to be the case that the 3D structure of an object is hard to determine from perceiving dots translating in depth alone (Braunstein, 1976) even though important information about the objects movement with respect to the observer can be extracted successfully in this situation (Regan and Beverley, 1979). However, translation perpendicular to the line of sight, that is traditional passive motion parallax, does seem to provide good information about the depth structure of objects, at least in some cases. The alternative "direct perspective" method for recovering strucure from motion which Ullman offers, would seem to be more applicable to the case of motion parallax. Although this method is not developed very far by Ullman, it is similar to some of the more general analyses of motion perspective to be discussed below.

Perhaps the greatest criticism of theories of the depth from motion process which are based on the KDE, is that they have moved away from a consideration of the overall motion perspective that accompanies movement of an observer in the everyday environment. In this situation, the whole visual array transforms as the observer moves, and provides information for the control of activity in an environment where surfaces and large objects are generally fixed. Although information about detached translating and rotating objects will obviously be of great importance, and our ability to use this information is very precise (Lee 1980), it seems likely that the visual system will have also developed techniques for using the information which accompanies self-movement in an essentially stationary world. From this viewpoint, several studies have attempted to provide a general, detailed, geometrical analysis of the information available to a moving observer, and several such analyses are now available (Nakayama and Loomis, 1974; Koenderink and van Doorn, 1976; Clocksin, 1980b; Longuet-Higgins and Prazdny, 1980). The empirical data, as we have seen, are equivocal and, at present, there has not been sufficient research to evaluate these recent models but they have increased understanding of the types of visual processes that might be involved in processing depth information from motion transformations.

2.5 Mathematical analyses of optic flow.

The movement of an observer in the environment is accompanied by a flow of differential velocities which, after Gibson, has been called motion perspective or optic flow. For locomotion parallel to a plane surface, the relative angular velocity between any two points on the surface is inversely related to the distance between them, as Helmholtz suggested. However, in general, the gradients of velocity are complicated by the presence of a radial expansion, the centre of which corresponds to the intersection between the observer's line of locomotion and the approaching surface. Hence, the pattern of velocities is determined both by the direction of the observer's locomotion and the slant of the surface and can, therefore, provide information about both these parameters. Several mathematical analyses of the relationship between velocity flow and 3D structure have now been derived.

The situation of locomotion towards a plane surface was analysed in the first mathematical description of optic flow by Gibson, Olum and Rosenblatt (1955). They described the optic flow present for an observation point moving in a constant linear direction toward a large textured fixed plane. They showed that several simple properties of the environment are represented in the optic flow in a straightforward way and therefore it might be possible for the visual system to perform the reverse operation of using optic flow properties to gain information about the environment. In particular, they showed that it should be possible to extract the relative depth of points on an approaching surface and that, although the observers speed and range are interdependent, the amount of time before the observer makes contact with the plane, can be computed directly from the flow parameters. This paper was important as an initial description of optic flow, however, it failed to provide details of how the suggested environmental properties could be extracted from the optic flow, and indeed, of whether they could in principle be specified by optic flow alone, for a human observer. In addition, the range of applicability of the analysis, for example, whether it would also apply to the case of a freely moving observer in a non-planar environment was not determined.

In 1974, Lee provided a more rigorous mathematical derivation of optic flow for the case of linear motion in a fixed textured environment. He demonstrated that range to a point was specified up to a scale factor and also pointed out that the boundaries between objects at different depths produced discontinuities in the optic flow with progressive occlusion and deletion of texture elements. Lee's emphasis was on the information in optic flow which would allow an observer to control locomotion in the environment, rather than on information about three-dimensional structure. He demonstrated that body-scaled information about self velocity and acceleration is potentially available, that is, information expressed in units such as the observers eye height above the ground. Lee also identified a simple optic variable, tau, which is the inverse of the rate of dilation of the flow at a point. This variable directly specifies the time to contact with the environmental point in that direction, provided that the current velocity of the observer is maintained. Lee has since demonstrated that this variable could potentially be used to control visually-guided activity such as diving, long-jumpimg and driving, and the empirical evidence suggests that human observers do, in fact, register and use this variable (Lee, 1976,1980). Because of his specific interest in visually guided activity, Lee's analysis is not concerned with how optic flow might specify three-dimensional structure, which is the aspect of flow of primary interest here. Apart from the range to a point, which may not be a useful measurement in itself, he does not specify how surface structure could be computed, for example, by determining the slope of the surface at any point or the depth edges between objects.

This aspect, however, was considered by Nakayama and Loomis (1974), who, as well as providing their own derivation of optic flow, went beyond this to consider how depth boundaries between objects could be determined. They suggested that this could be done by "convexity" mechanisms which computed the difference in velocity between local areas and their surrounds. This idea of simple local mechanisms detecting velocity differences over local areas has proved important in many recent models. If the structure of the flow field over a local area can provide information about the depth edges within that area, which can then be pooled with information from the rest of the field, then fairly simple physiological mechanisms could perform the basic processing needed to extract structure from optic flow.

In a rather different type of analysis, using differential vector geometry, Koenderink and van Doorn (1976) have shown that several aspects of the local structure of the optic flow are relatively simple to compute using local mechanisms. In particular, they show that computing the deformation, divergence and curl of the local flow field could be accomplished relatively easily by such mechanisms, and that combinations of these computations could provide sufficient information to specify the surface orientation at any point in the environment. In addition, these aspects of local structure are invariant with respect to rotation of the flow field and are particularly useful because they can extract depth information even when the observer is moving along a curvilinear path and making rotational eye movements. This analysis is applicable, therefore, to a more general case of observer motion in the environment than are those discussed previously. It is important to note, however, that this invariance with respect to rotation of the flow field is only applicable if the projection coordinates of the computed optic flow are oriented so that the direction of the coordinate frame is known with respect to the observer's direction of motion. This means that to use optic flow in the general case observers would have to determine their instantaneous direction of movement prior to computing three-dimensional structure. In addition, Koenderink and van Doorn (1975) have shown that even for the case of an environment containing moving objects, extracting the deformation, divergence and curl of the flow field would still be computationally useful, and moreover, they show that the singularities in the optic flow, such as peaks, saddle points and specular points, provide a topological map of the environment. Koenderink and van Doorn's work provides the most complete description of how the layout of the environment is represented in the structure of optic flow. The way in which the optic flow might actually be related back to the environmental structure is, however, only discussed superficially, so that, although it is clear that the optic flow field could be a very rich source of visual information, the details of how this information might be extracted using local processing mechanisms are not provided.

More recently, Clocksin (1980a, 1980b) has developed a computational model for processing information from optic flow, where the applicability of the model to the human visual system is carefully considered. Using the simplified case of an observer translating in a fixed environment, he has derived a method whereby the slant of a surface at any point can be computed and he has shown how, from this information, a relative depth map of the environment can be produced. The location and type of depth edges in the environment can then be computed from a differential analysis of the relative depth map. The original and important contribution of this study is that Clocksin has also provided details of a simple physiological model which could carry out the necessary computations and has implemented the model on a computer, using an algorithm which has, so far, produced results compatible with the limited empirical data.

A different computational model by Prazdny (1980) has also been implemented and again produced results compatible with those obtained from human observers. This analysis covers the general case of curvilinear motion through a rigid environment, and Prazdny has shown that all the parameters of the observers own motion (speed and direction) can be computed from local neighbourhoods of five points in an instantaneous velocity field. Once the direction of the observers motion has been determined then the relative depth map, and, finally, local surface orientation can be computed. In the computer simulation, large neighbourhoods, densely textured environments and reasonable velocities of observer motion produced the most accurate results. This model is primarily concerned with determining the parameters of egomotion from optic flow rather than placing the emphasis on the extraction of structural information.

Finally, a sophisticated mathematical study has been carried out by Longuet-Higgins and Prazdny (1980). They derive an original mathematical formulation for the case of general motion through a fixed environment. Firstly, they show that, generally, the velocity flow field contains both a translational and rotational component. In order to determine the underlying environmental structure, which can be computed from the translational component, it is necessary to have some means of extracting the rotational component from the overall flow. To do this, the direction of translation must be obtained, and they suggest that this can be done by looking at the relative angular velocity between the projections of two points, at different distances but in roughly the same visual direction. Their analysis can be extended to deal with an environment of moving objects if a separate computation of structure is carried out on each object. In general, they demonstrate that it is possible to compute the relative motion of an object and the shape of the surface of the object, from the first and second spatial derivatives of the velocity field in the neighbourhood of the projection of a point on the object. In this analysis, therefore, the local surface structure of the object is computed directly and not subsequent to the computation of relative depth as in many of the previous analyses that have been discussed. Since the analysis depends on the extraction of first and second spatial derivatives at a point, planar surfaces present a special problem as here the second derivative is zero. However, in general, the computation suggested by this analysis, could be carried out by local mechanisms in the neighbourhood of a point, over an area of the flow field large enough to allow the second derivative to be computed with sufficient accuracy. Longuet-Higgins and Prazdny also point out that there are four specific combinations of the first spatial

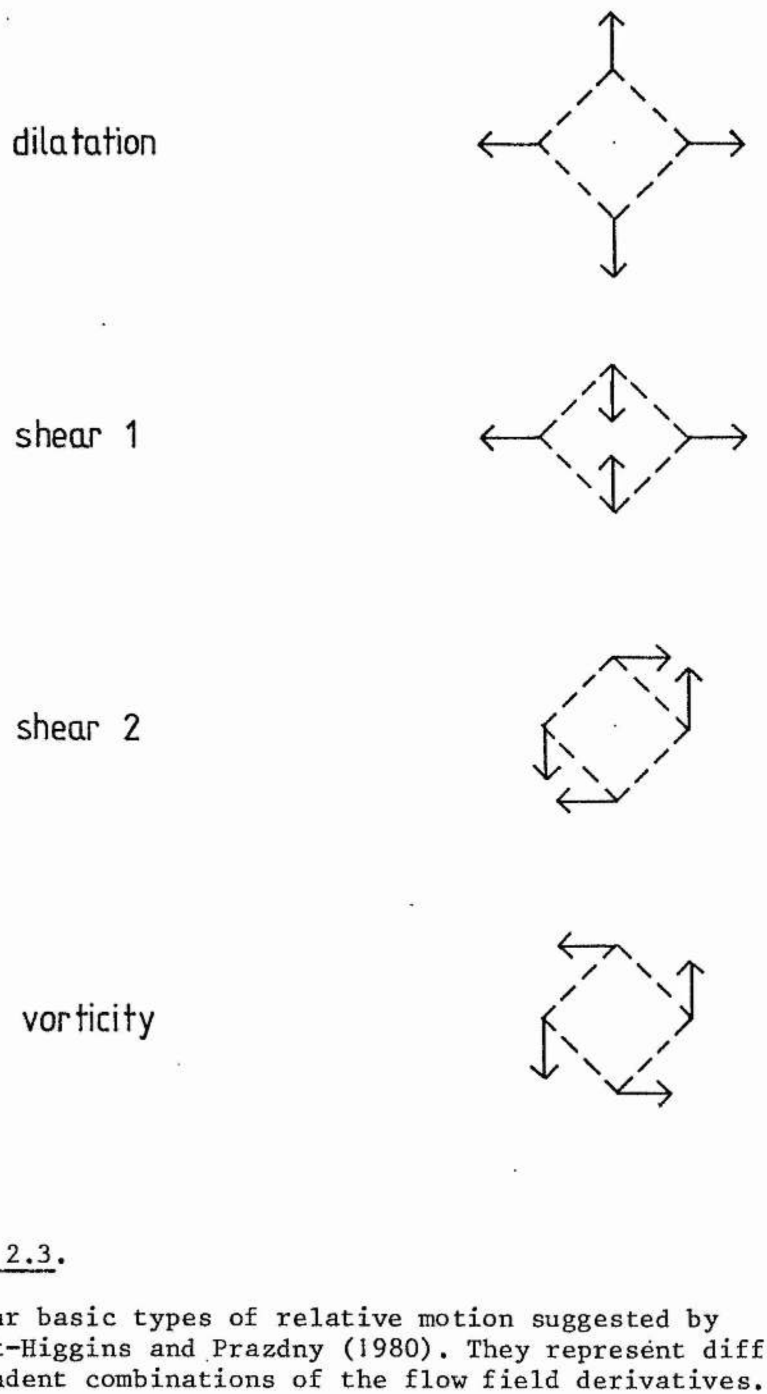


Figure 2.3.

The four basic types of relative motion suggested by Longuet-Higgins and Prazdny (1980). They represent different independent combinations of the flow field derivatives.

derivatives of the flow field which could be simply computed and which would be invariant to rotation of the flow field. These four combinations would pick up expansion, shear and vorticity components of surface texture elements over a local area as illustrated in Figure 2.3. (These components are similar to the invariants of local structure described by Koenderink and van Doorn.) Mechanisms tuned to detect such combinations of the flow field derivatives would, therefore, be particularly useful to any system that wished to extract information about depth from patterns of relative motion.

2.6 The information available in optic flow.

Although the mathematical analyses of optic flow described above differ in the details of the mathematical derivation and in their underlying assumptions, they do share many similar properties. This section provides an example of one possible derivation of the parameters of optic flow and outlines a model of how the available information might be extracted. The present analysis is based on Clocksin (1980a, 1980b) and provides a general flavour of this type of approach as well as a description of a mechanistic model of possible physiological mechanisms.

Initially, consider the general case of an observer moving along a curvilinear path in an environment of rigid, opaque objects and surfaces, some of which may move with respect to the observer. As illustrated in Figure 2.4, the optic flow on a spherical projection surface centred on the point of observation, O, can be mathematically described in the following way. Each element, P, in the environment

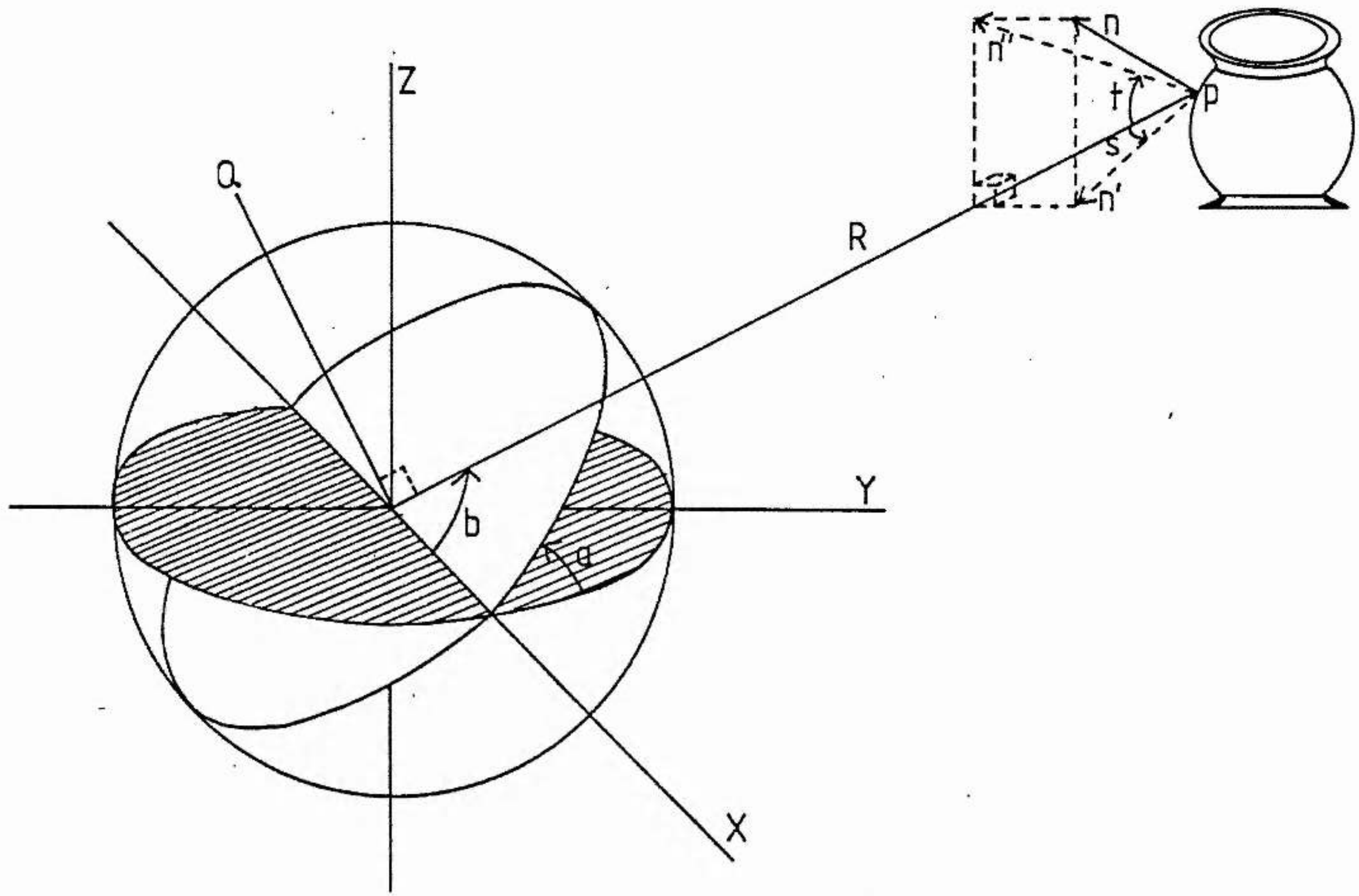


Figure 2.4.

The generalised optic flow pattern is defined as the instantaneous angular velocity that each point P makes on a unit sphere centred around an XYZ coordinate system. The direction of P can be defined by a and b which represent the angles of meridian and eccentricity.
The slope of the surface at P can be represented by the normal to the surface, n, which has two components, n' and n'' in two orthogonal planes RX and QR. The slope at P can therefore be represented by the angles s and t.

has an instantaneous angular velocity on the unit projection sphere consisting of two components, $\dot{a}$ and $\dot{b}$, which represent the instantaneous change in the angles of meridian, a, and eccentricity, b. The most general description of optic flow is given by the following two equations which are derived in Figure 2.5.

$$\dot{a} = \dot{z}\cos a - \dot{y}\sin a)/r\sin b$$

and $$\dot{b} = ((x\dot{x}+y\dot{y}+z\dot{z})\cos b - r\dot{x})/r^2\sin b$$

The above equations provide a description of the optic flow on a spherical projection surface. In order to use the optic flow to provide information about the environment, it is necessary to reverse the mapping and, for example, to solve for r. In order to do this it is necessary to find the values $\dot{x}$, $\dot{y}$, and $\dot{z}$. These values contain both a component due to the movement of the observer and to the movement of the surface and these two components cannot easily be separated in the general case.

However, if we consider a restricted case of an observer translating through a fixed environment, the nature of the optic flow becomes very simple. In particular, if the x axis of the coordinate system is oriented along the direction of translation and the observer's speed is S, then $\dot{y}=\dot{z}=0$ and $\dot{x}=-S$. The optic flow function f(a,b) therefore becomes

$$\dot{a} = 0 \quad : \quad \dot{b} = S\sin b/r \qquad (3)$$

Hence for translation through a fixed environment, the optic flow is mathematically simple and the above function is a formal

Figure 2.5.

The generalised optic flow is the instantaneous angular velocity that each point P makes on the unit sphere (Figure 2.4). Each angular velocity has two components $\dot{a}$ and $\dot{b}$.
$\dot{a}$ and $\dot{b}$ give the generalised components of instantaneous optic flow with respect to the angles of meridian and eccentricity for any point P at distance r and position (x,y,z) with respect the origin of XYZ.

In general – $x = r\cos b \;:\; y = r\cos a.\sin b \;:\; z = r\sin a.\sin b = y\tan a$

since $z = y\tan a$

$$\dot{z} = \dot{y}\tan a + y\sec^2 a.\dot{a}$$

$$\Rightarrow \quad \dot{a} = \dot{z} - \frac{\dot{y}\tan a}{y\sec^2 a}$$

since $y = r\cos a.\sin b$

$$\Rightarrow \quad \dot{a} = \dot{z} - \frac{\dot{y}\tan a}{r\cos a.\sin b.\sec^2 a}$$

i.e. $$\dot{a} = \frac{\dot{z}\cos a - \dot{y}\sin a}{r\sin b}$$

since $x = r\cos b$

$$\dot{x} = \dot{r}\cos b - r\sin b\,\dot{b}$$

$$\Rightarrow \quad \dot{b} = \frac{\dot{r}\cos b - \dot{x}}{r\sin b}$$

since $r^2 = x^2 + y^2 + z^2$

$$\dot{r} = \frac{x\dot{x} + y\dot{y} + z\dot{z}}{r}$$

$$\Rightarrow \quad \dot{b} = \frac{(x\dot{x} + y\dot{y} + z\dot{z})\cos b - r\dot{x}}{r^2\sin b}$$

expression of Gibsons insight that during locomotion texture elements flow along lines of longtitude on a projection sphere whose poles are located along the direction of motion (see Figure 2.2c). From equation (3), the range, or distance, to the point P can be obtained up to a scale factor and determined absolutely if the observers speed is known. However, without knowing the speed, the surface orientation at P and the relative depth between different environmental points can be determined directly from the optic flow in the following way.

In general, the slant of a surface at a point can be represented by the normal to the surface at that point and can be completely defined by two component of slant, s and t, which represent the angle of the normal with respect to the planes of meridian and eccentricity (Figure 2.4). As derived in Figure 2.6, the two components of slant can be directly determined from the optic flow by considering the first spatial derivatives of the flow in the two directions, a and b, so that,

$$\tan s = \cot b - d/db \log f \quad : \quad \tan t = -d/da \log f \qquad (4)$$

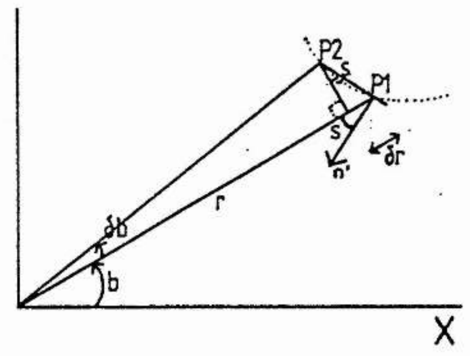
Finally, the presence of depth edges and their type, convex, concave, occluding, revealing etc., can be obtained from looking at the Laplacian of the optic flow function, which measures the second spatial derivatives with respect to a and b.

$$L^2 f = d^2f/da^2 + d^2f/db$$

The singularities of this operation occur in a specific distribution, a signature, which depends on the type of the physical edge. This is analogous to the use of the Laplacian operator in computational models designed to detect luminance edges in pictures

Figure 2.6.

As shown in Figure 2.4, the normal to the surface at P can be represented by two angles s and t which represent the components of slant in two orthogonal planes. The components s and t can be computed trigonometrically as follows.



In the limit $\tan s = \dfrac{\delta r}{r\delta b}$

Similarily in the orthogonal plane

$$\tan t = \frac{\delta r}{r\delta a}$$

Equation (3) gives : $r = \dfrac{S \sin b}{f(a,b)}$

Differentiating - $\dfrac{\partial r}{\partial b} = \dfrac{S(f \cos b - \sin b . \partial f/\partial b)}{f^2}$ and $\dfrac{\partial r}{\partial a} = \dfrac{-(S \sin b . \partial f/\partial a)}{f^2}$

Hence $\tan s = \dfrac{S(f \cos b - \sin b \, \partial f/\partial b) / f^2}{S \sin b / f}$ $\tan t = \dfrac{-(S \sin b \, \partial f/\partial a) / f^2}{S \sin b / f}$

Simplifying $\tan s = \cot b - \dfrac{\partial}{\partial b} \log f$ $\tan t = -\dfrac{\partial}{\partial a} \log f$

(Roberts, 1965). Each different type of edge, concave, convex, occluding, revealing, etc., has its own unique form when the above computation is carried out.

In summary, this analysis suggests that, at least in the case of translation through a fixed environment, it is possible to compute the slant of surfaces in the environment and the presence and type of depth edges. A further question is whether this computation could be feasibly carried out. In general, for a computation to be feasible for the visual system, it is necessary for it to be based on simple, local, discrete computations which can be carried out by neural units. Clocksin has suggested that it would be possible for a simple network of velocity sensitive mechanisms to carry out the computation of 3D structure from optic flow, and he has implemented a computer algorithm which simulates the performance of such a network. In order to compute structure from optic flow the model requires that mechanisms for detecting retinal velocity exist within the system and that the a/b coordinate system can be established from the flow data (so that the retinal direction along which computations are made at each point, can be determined).

The presence of velocity sensitive mechanisms in the human visual system has been indicated psychophysically and physiologically in recent years (Pantle and Sekuler, 1968; Tolhurst et al., 1973), and these mechanisms have been found to be directionally selective. In Clocksin's model such velocity sensitive mechanisms (VSM's) form the basis for the computation. At each retinal location the VSM with the highest firing rate signals the direction of the velocity at that point and inhibits other VSMs sensitive to other directions. At a higher level the VSM's are grouped together into units with elongated receptive fields as illustrated in Figure 2.7. These higher level units receive inputs from VSM's which have spatially adjacent receptive fields. It can be seen that, for movement in a fixed environment, higher level units where the direction of movement at each point is parallel to the orientation of the receptive field, will be oriented along lines of constant meridian (a) while those where the direction at each point is orthogonal, will be oriented along lines of constant eccentricity (b). All other units are excluded from further processing (Figure 2.8). The higher level units which are active at any one time therefore change from instant to instant as the observer moves in the environment and the pattern of optic flow changes. Hence the model fulfils the second requirement mentioned above, that the a/b coordinate system be established from the flow data. Once the VSM's have been grouped into these higher level units, the gradient of velocities along the length of the receptive field can then be computed using a simple differencing operation. This provides the terms dlogf/da and dlogf/db in equation (4) and the output of this stage of processing is then the two values (tant) and (cotb -tans). The value (cotb) depends on the movement of the observer and will be equal for all parts of the field. It could therefore be determined by computing over a larger area. When the observer views surfaces at 90 degrees to the direction of motion (cotb) is of course zero. The final output of the computation would be both components of slant, s and t, that is, the angles of slope with respect to the meridional and eccentric planes which uniquely define the slope of the surface at a point.

In addition to computing the surface slant at a point the model can also detect depth edges by computing the second spatial differences

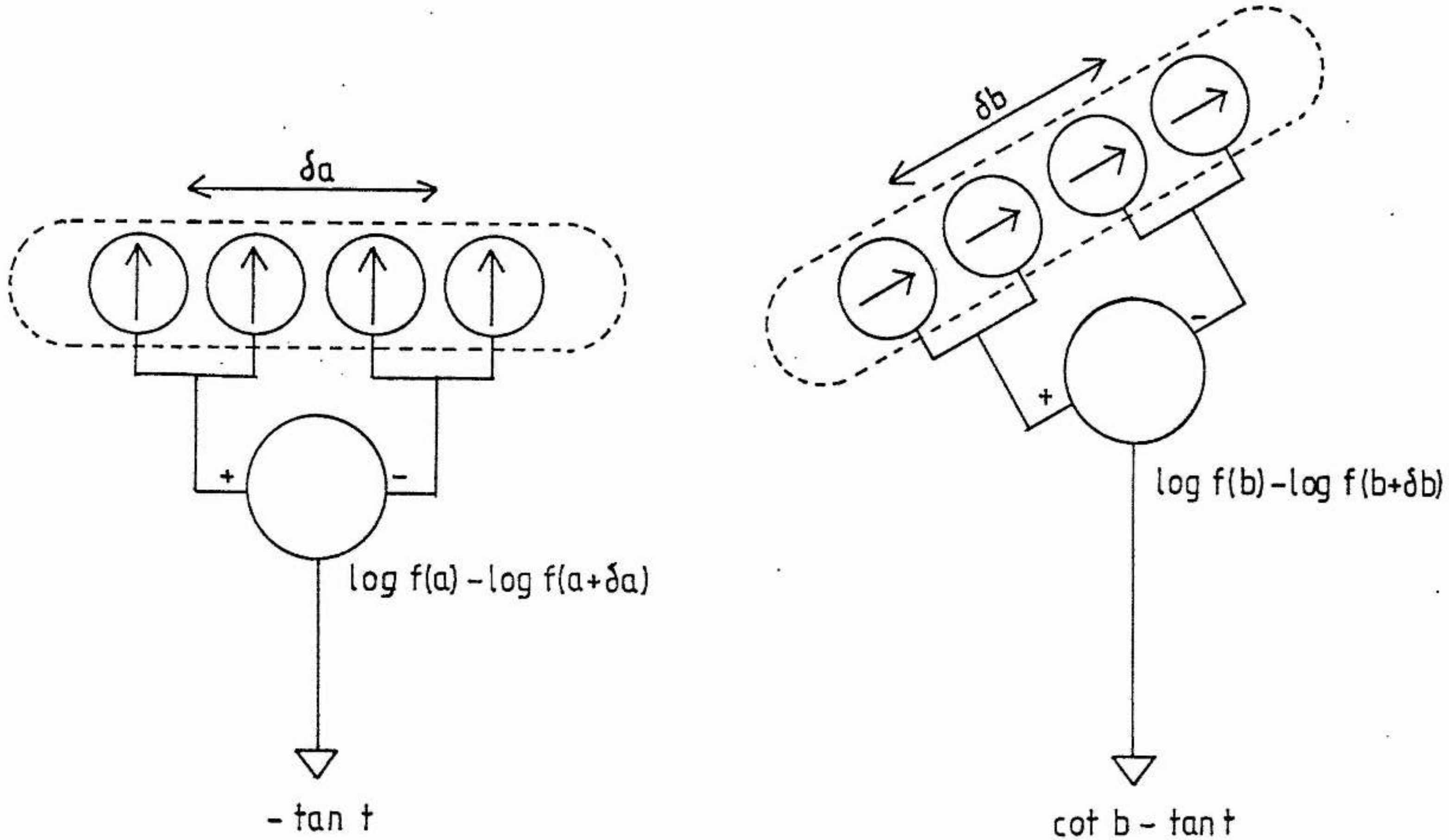
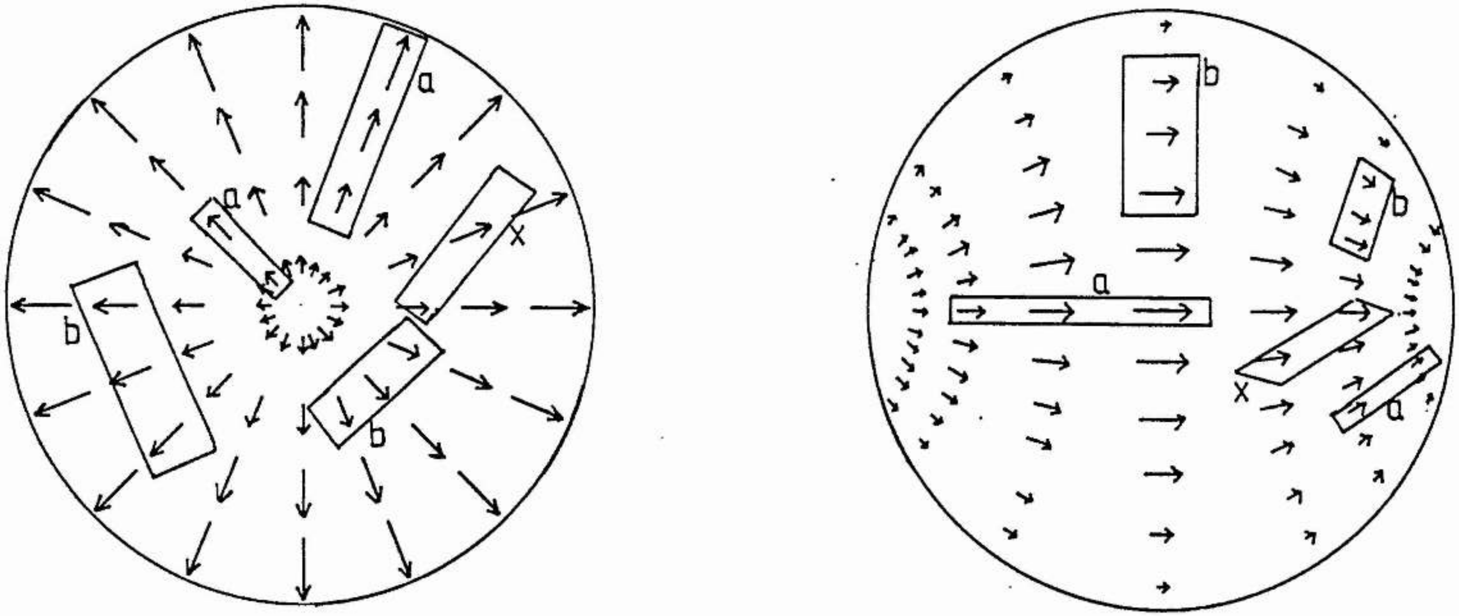


Figure 2.7.

A physiological model which extracts the change in velocity along two directions corresponding to lines of constant meridian and eccentricity. The output of the higher level units give the components of slant of the surface in that direction with respect to the observer.



<u>Figure 2.8.</u>

Depending on the particular flow pattern the higher level receptive fields shown in Figure 2.7, either lie along lines of constant a or constant b or neither (x). The latter units are discarded from further processing.

in velocity along a and b. When this second difference is very large, the presence of an edge is signified. The type of edge present can be determined from the nature of the flow differentials around the edge. Detectors responding to the type of edge present would be analogous to the on and off brightness detectors in the luminance domain which signal different types of luminance edge. This computation of second spatial differentials is similar to the operation that would be carried out by the convexity operator suggested by Nakayama and Loomis.

Finally, Clocksin has produced a computer implementation which simulates this type of physiological model. Predictions that follow from the model are that absolute distance cannot be computed in the absence of information about the observers speed, and that edge and slope detection should show increasing threshold with eccentricity, lower speeds and smaller depth changes. The computer implementation produces results which are in accordance with those found psychophysically for human observers, however, the amount of adequate empirical data is very small and does not provide an adequate test of the model.

Chapter 3 Can Motion Parallax Act as an Effective Source of Information about Depth and Distance ?

3.1 Introduction.

There have been many empirical studies which have attempted to investigate whether motion parallax can be used effectively to determine the distances to different objects and the depth relationships within them. These studies were reviewed in the previous chapter where it was noted that the results have been equivocal. Some studies have suggested that motion parallax is only a weak and unreliable source of depth information which is easily overidden by information from other sources, and which cannot even be used to ascertain unambiguously the relative depth of two objects or surfaces (Gibson and Carel, 1952; Eriksson, 1972; 1973; Gogel and Tietz, 1973; 1974; Farber and Mcconkie, 1979). Other studies have, however, found that motion parallax can be used effectively (Gibson et al., 1959; Flock, 1964; Braunstein, 1966; 1976; Hell, 1978) and can, in some situations, provide accurate information about absolute as well as relative depth (Johansson, 1973; Ferris, 1972). The contradictory nature of these empirical studies was found to be surprising in light of the ease with which human observers can use the kinetic transformations which accompany rotation of an object, to specify the 3D structure of the object (Wallach and O'Connell, 1953; Braunstein, 1976; Caelli, 1980), and in light of the theoretical potential of motion parallax to act as an effective source of information about depth strucure (Gibson et al., 1955; Nakayama and Loomis, 1974; Koenderink and van Doorn, 1976; Longuet-Higgins and Prazdny, 1980;

Clocksin, 1980b).

It was suggested that part of the disagreement found in the literature reflected the wide variety of stimulus conditions used to provide motion parallax information. Firstly, parallax seemed to be less effective if only a few points or velocities were used in the stimulus display, and this suggests that a dense texture containing a gradient of relative velocities would be a more optimal stimulus for the effective use of parallax information. Moreover, a situation which involves a flow of velocities is more similar to the optic flow which accompanies real movement of an observer in the environment. Finally, studies which have used parallax situations which required active movement of the observer have generally found positive results. Therefore, an adequate situation for studying the effectiveness of motion parallax information seems to be one where textured patterns containing whole gradients of relative motion are used as stimuli, and where the parallax information is provided by active movement of the observer.

Another limitation of many of the previous studies was that the experimental technique did not allow the parameters of the optic flow to be carefully varied so that the detailed psychophysical characteristics of the motion parallax processing system could be measured. In most cases, the techniques of stimulus generation were not flexible enough for the production of complex patterns with specific characteristics. In addition, there was often no adequate response measure and observers were merely required to report whether depth was present in the stimulus or to make verbal estimates of the amount of depth. This technique has been shown to be unreliable in many situations (Gogel, 1979a).

Finally, previous studies also varied in the extent to which other cues to depth and distance were present in the stimulus situation. Cues such as accommodation, relative size and perspective were present in some studies. In many others, motion parallax information was confounded with occlusion effects which are known to provide strong information for depth separation (Kaplan, 1969). To investigate the visual system's ability to use parallax information it is necessary to use a technique which allows motion parallax to be presented in isolation from all other sources of depth information.

Over the last twenty years, a large amount of fruitful research has investigated the nature of the visual systems ability to use depth information from binocular stereopsis. This has led to a firm psychophysical data base from which detailed models of the stereoscopic process have been developed (Nelson,1975; Marr and Poggio, 1979; Mayhew and Frisby, 1980). This large research effort was primarily motivated by the development of computer generated random dot stereograms which were first used by Bela Julesz in the early 1960's (Julesz, 1960; 1971). A random dot stereogram consists of two nearly identical random dot patterns which appear flat when viewed singly. However, when the two halves are viewed stereoscopically, one to each eye, the slight differences between the positions of the dots in the two patterns give rise to the perception of a three-dimensional figure. Hence in a random dot stereogram there is no monocular information about the form of the three-dimensional surface. The form is specified solely by the binocular disparities between the random elements of texture in the two patterns. The importance of this technique, therefore, is that it allows binocuolar stereopsis to be studied in isolation from other depth cues. Moreover, random dot stereograms can be used to specify any 3D surface in a precise way and so provide a flexible tool for investigating the parameters of stéreoscopic vision.

An adequate investigation of the use of motion parallax information by the visual system required a technique, analogous to the use of random dot stereograms for stereopsis, which allowed motion parallax to be studied in isolation from other sources of depth information. That is, a technique was needed where the only source of depth information was the pattern of relative motion accompanying movement of the observer or the object, and where, without this movement, there was no information about three-dimensional form. In addition, it was necessary that the technique allowed many different three-dimensional figures to be portrayed and that the parameters of the motion transformation could easily be manipulated.

3.2 The motion parallax display.

An experimental technique which could simulate the motion parallax information produced both by movement of an observer in the environment and by movement of a 3D object with respect to the observer, was developed by Rogers and Graham (1979). This technique isolated motion parallax from other potential cues about depth and provided a basis for a detailed analysis of the use of motion parallax information. In Figure 3.1 the experimental set-up is shown in diagrammatic form.

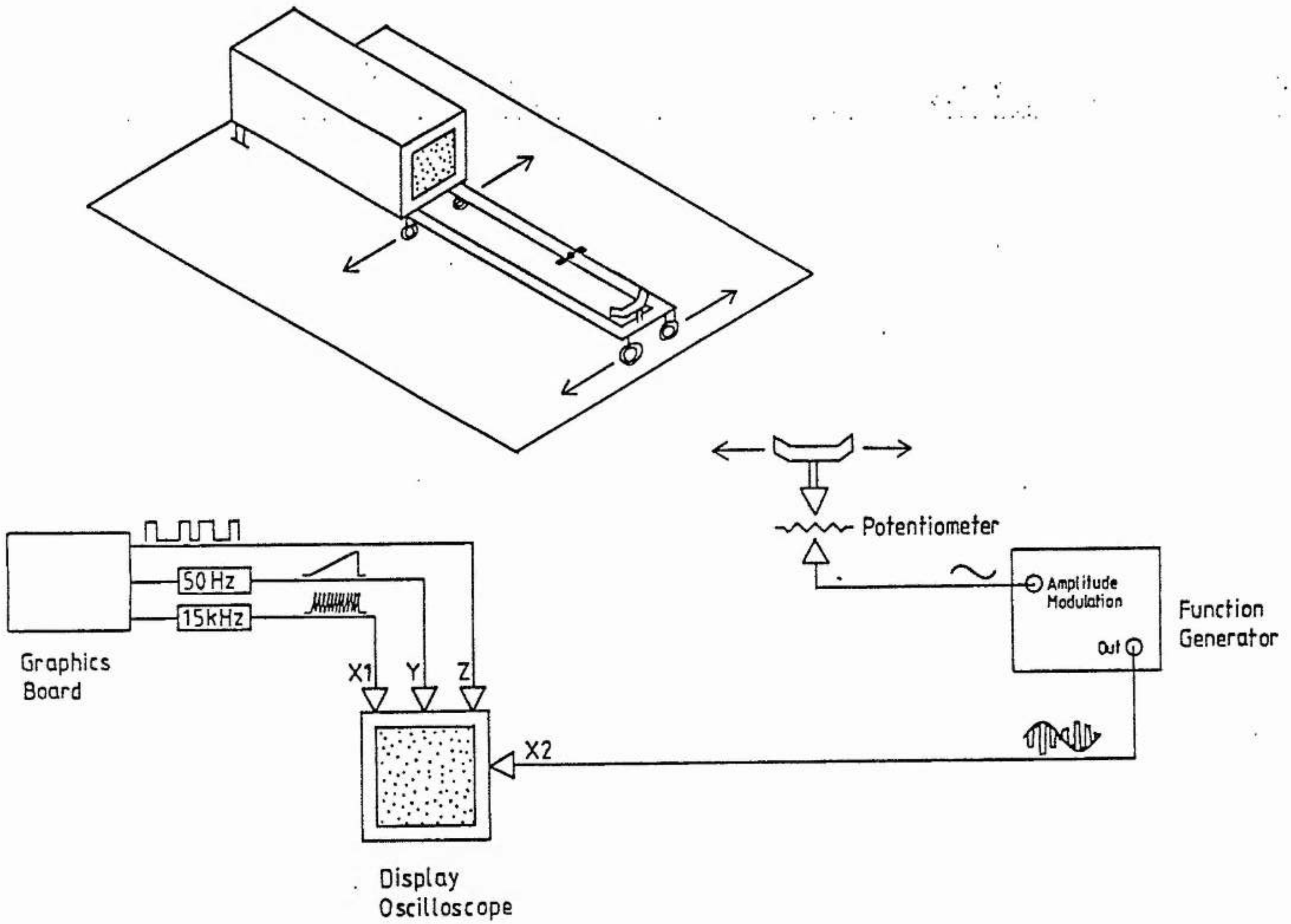


Figure 3.1.

The motion parallax display: An observer moves laterally on a chinrest while viewing a random dot pattern on an oscilloscope. The pattern is produced using a raster technique and a graphics board attached to a microcomputer. Relative motion is introduced into the pattern by an additional line signal the amplitude of which is continuously modulated by a voltage from a potentiometer attached to the arm of the chinrest. Alternatively the observer remains stationary while the oscilloscope translates across the line of sight.

A random dot pattern displayed on an oscilloscope screen was used to provide the motion parallax information. Observers viewed the random dot pattern while moving from side to side on a chinrest. The aim was to simulate the motion parallax information that would be produced by a physical three-dimensional surface in the plane of the oscilloscope screen, as the observer moved from side to side while viewing the surface. To do this, the two-dimensional random dot pattern displayed on the screen, was systematically distorted as the observer moved, in a way which provided the appropriate relative motion transformation.

To understand how the stimuli were produced, it is helpful to consider the relative motion transformation that occurs when an observer moves laterally while viewing a simple three-dimensional surface containing a single bar standing out in front of a background. Such a surface is illustrated in exaggerated perspective in Figure 3.2a. When this surface is viewed from the left, the centre band of dots is displaced to the the right with respect to the surrounding dots, and, as the observer moves to the right, the centre band of dots becomes progressively shifted to the left (Figure 3.2b). Therefore, to simulate the parallax information provided by this surface, a relative displacement between the centre band of dots and the surround must be introduced into the two-dimensional pattern as the observer moves. That is, when the observer moves from left to right, the centre band of dots in the pattern must move to the left with respect to the surround, and as the observer moves from right to left it must move to the right. To do this the movement of the centre band of dots must be linked to the movement of the observer's head. In the present situation, the appropriate relative movement was produced by adding a distortion

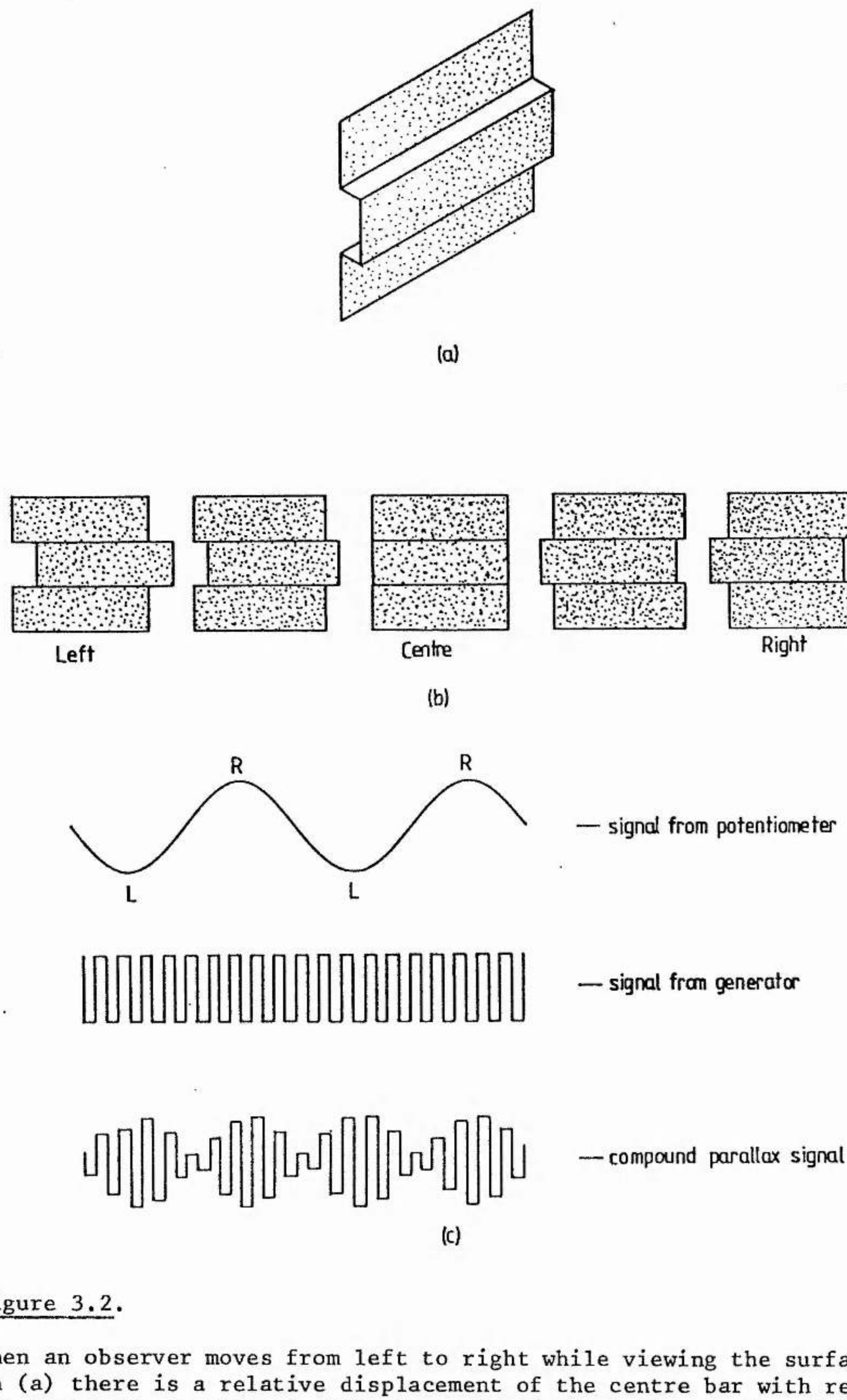


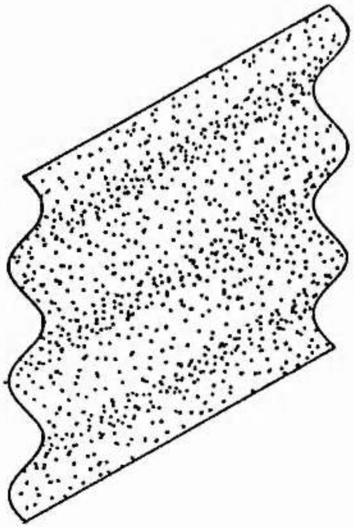
Figure 3.2.

When an observer moves from left to right while viewing the surface shown in (a) there is a relative displacement of the centre bar with respect to the surround, as shown in (b). Hence to simulate the parallax information provided by this surface there must be relative motion between the centre bar and the surround as the observer moves. The appropriate parallax signal can be produced by modulating, or multiplying, a square waveform of an appropriate frequency by the voltage signal from the potentiometer which follows the observer's sinusoidal movement from side to side (c).

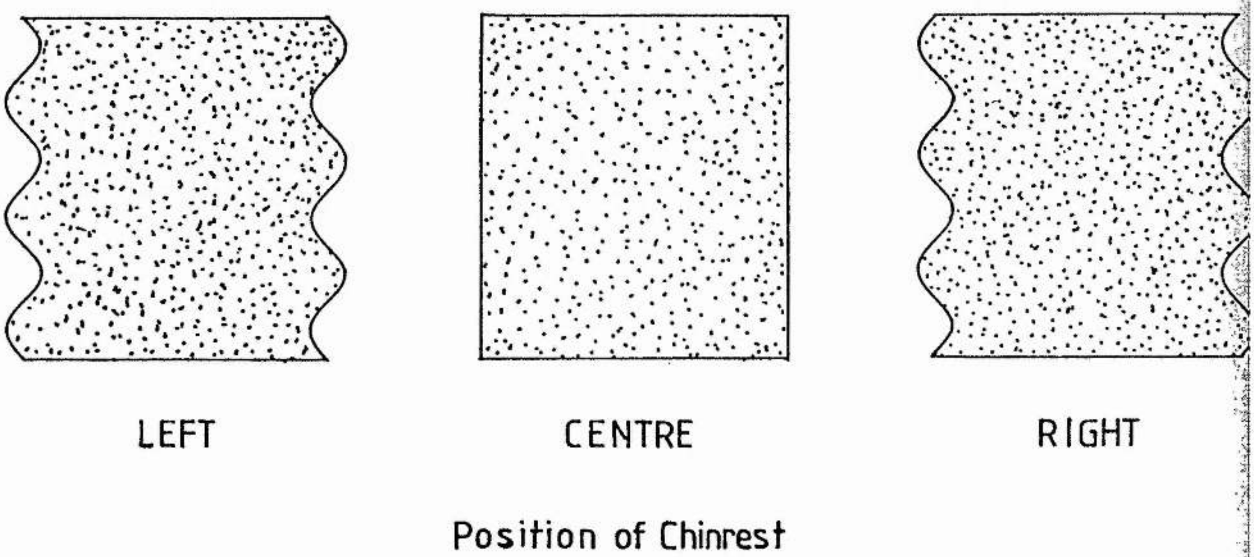
signal to the X input of the oscilloscope which displaced the centre band of dots. A function generator was used to produce a square wave signal of the appropriate frequency to shift the centre band of dots with respect to the surround. It was then necessary to link the displacement of the centre band to the movement of the observer. This was done by modulating the amplitude of the square wave signal with a signal which monitored the movement of the observer. For the present display the movement of the observer was monitored by a potentiometer attached to the arm of the chinrest. As the observer moved laterally from side to side the voltage from this potentiometer produced a sinusoidal signal at the frequency of the head motion. This signal was used to amplitude modulate the square wave signal from the function generator, an operation which effectively multiplied the two signals together (Figure 3.2c). The resulting compound distortion signal was then fed to the X input of the oscilloscope. In effect, this arrangement produced a continuous relative movement between the centre and surround of the random dot pattern, and this movement was exactly in step with the movement of the observer. When the observer stopped moving, the display was static and there was no information as to the form of the three-dimensional surface specified by the parallax transformation.

To simulate the motion parallax information provided by a more complex depth surface, distortion signals were composed where the underlying waveforms were of different shapes. Again the amplitude of the signal was modulated according to the position of the observer. For example, to simulate a corrugated depth surface where the depth changed continuously from the top to the bottom of the surface in a sinusoidal manner, a sine wave rather than a square wave signal was taken from the function generator. This signal was multiplied by the signal from the potentiometer which monitored the movement of the observer. As the observer moved from side to side, horizontal bands of dots corresponding to the troughs of the corrugation moved in the same direction as the observer, while bands corresponding to the peaks, moved in the opposite direction. Between the peaks and the troughs, the amount and direction of relative motion followed a sine wave profile (Figure 3.3). In the actual display the random dot pattern was always slightly larger than the oscilloscope screen so that the edges of the pattern (shown in the figures for illustrative purposes) were never visible, and could not provide information about the shape of the simulated three-dimensional surface. When the observer was stationary all that could be seen was a random dot pattern filling the screen.

By varying the shape of the distortion signal, different types of depth surfaces could be simulated and some examples are shown in Figure 3.4a. In addition to the shape of the wave form two other parameters could be varied. The temporal frequency of the the distortion signal could be altered so that a larger or smaller number of cycles of the waveform appeared on the screen. For corrugated depth surfaces this manipulation had the effect of varying the spatial frequency of the depth corrugation, that is, the number of depth corrugations per degree of visual angle. Secondly, increasing the gain of the amplitude modulation, increased the extent of relative movement between different parts of the pattern, for a given displacement of the chinrest. Hence, by varying the overall ampitude, depth surfaces containing varying amounts of relative depth could be simulated (see Figure 3.4b).



(a)



(b)

Figure 3.3.

To simulate the sinusoidally corrugated depth surface illustrated in (a), the random dot pattern is distorted according to the position of the observer's head on the chinrest, as shown in (b). Hence, in step with the observer's movement from side to side there is continuous relative motion between the different rows of the pattern.

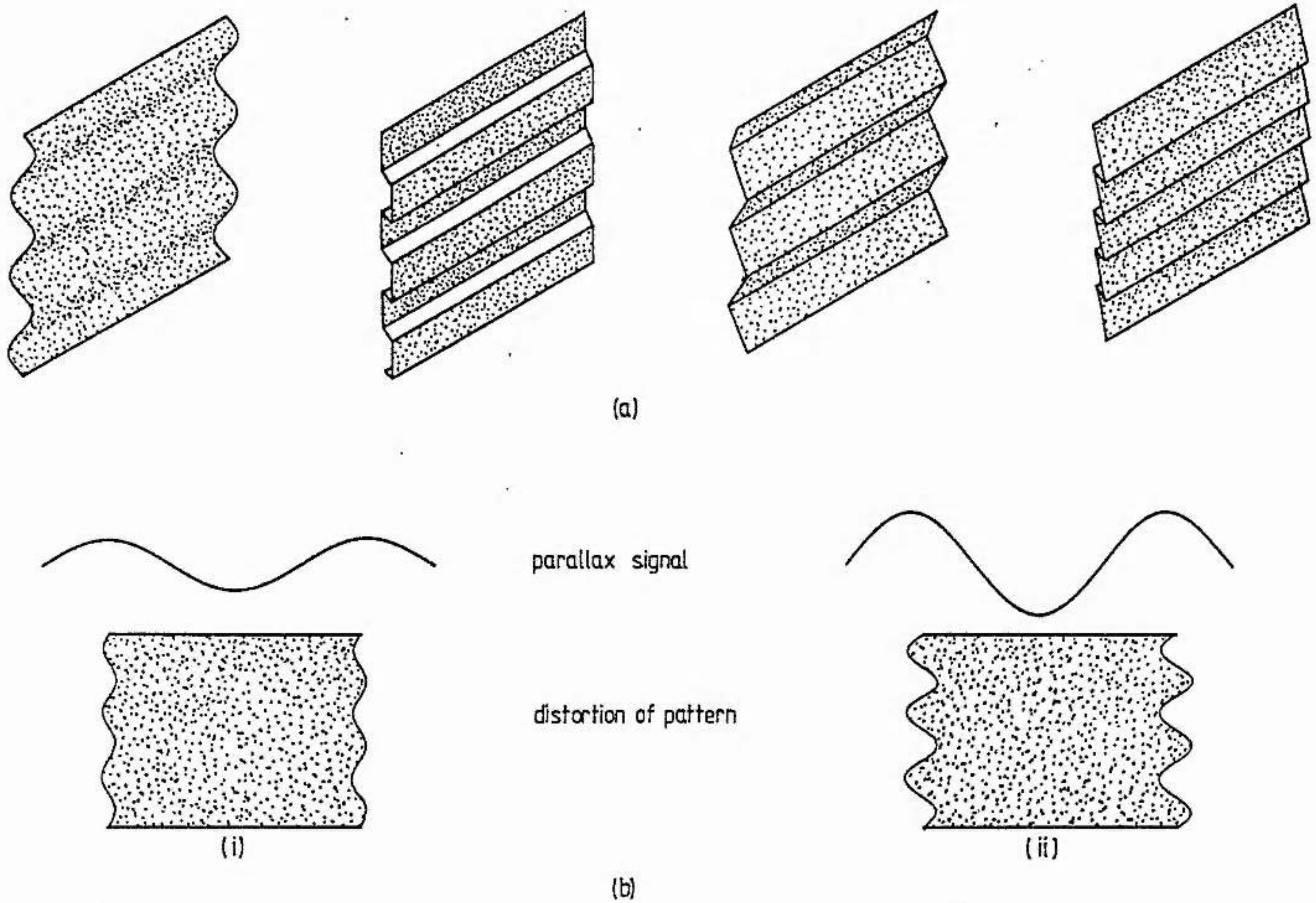


Figure 3.4.

(a) Corrugated depth surfaces with sine, square, triangle and ramp shaped depth profiles.
(b) Increasing the gain of the parallax signal increases the amount of relative motion in the random dot pattern for a given amount of head movement. This simulates a depth surface with a greater peak to trough depth difference.

The experimental arrangement described so far simulates the motion parallax information which accompanies active movement of the observer in the environment, and will be called an "active" parallax situation. From the geometry of the situation, and as described in the last chapter, parallax information is also available when the observer remains stationary and three-dimensional objects move across the line of sight. The motion parallax information available in such a "passive" parallax situation was also simulated in the present experiments. To do this, the observer remained stationary while viewing the random dot pattern on the oscilloscope screen, and the oscilloscope, which was mounted on castors, was moved laterally from side to side across the observers line of sight. As before, a distortion signal was added to the random dot pattern, which produced relative motion between different parts of the pattern. This time, however, the amplitude of the distortion signal was modulated by the movement of the oscilloscope, rather than by the movement of the observer. A potentiometer monitored the movement of the oscilloscope, and the voltage from this potentiometer was multiplied by the signal from the function generator in the same way as before. As the oscilloscope moved from side to side, there was a continuous relative displacement between different rows of dots, which was in step with the movement of the scope, and which simulated the relative motion transformation that would have been produced if the front surface of the scope had been three-dimensional. Again, by varying the shape, temporal frequency and gain of the amplitude modulation three-dimensional surfaces with different characteristics could be produced. In the following experiments, the experimental apparatus could therefore be used to investigate the use of motion parallax information in both active and passive situations.

3.3 Preliminary qualitative observations.

An initial qualitative study was carried out to determine whether the simulated motion parallax information, provided using the technique described above, could actually be used by human observers to determine the shape and three-dimensional structure of the simulated surfaces. The initial study used twelve naive observers (Graham, 1978; Rogers and Graham, 1979) but the results have since been confirmed on at least a hundred naive subjects during laboratory demonstrations.

In the active parallax situation observers were required to move from side to side on the chinrest at their own preferred rate (usually about 15-20cm/sec). In the passive parallax condition they remained stationary and viewed the transforming pattern as the scope moved across their line of sight. In both conditions observers viewed the random dot pattern monocularly and were allowed to scan the pattern freely. The lateral excursion of the observer or the oscilloscope was restricted to 15cms. Observers were asked to report the phenomenal appearance of the random dot pattern before, during and after the movement.

The results were very clear. Before moving, the pattern appeared as a flat two-dimensional random dot plane. However, after just one or two movements of the head or scope, all observers reported that the random dot pattern appeared to be a stationary, solid, three-dimensional surface attached to the oscilloscope screen. The relative motion present in the random dot pattern was not perceived and the three-dimensional surface appeared to be completely rigid. The depth impression obtained on viewing these parallax surfaces was found to be similar to that obtained on viewing a random dot stereogram portraying a stereoscopic surface. When the observer stopped moving the random dot pattern again appeared completely flat. Without the relative movement the observer could not report the shape of the simulated surface indicating that motion parallax was the only source of form information available in the display. The phenomenal impression of the depth surface was very similar for both active and passive parallax conditions.

Observers were then presented with the four different types of parallax surfaces shown in Figure 3.4a. The surfaces were randomly presented with one of three spatial frequencies (one, three or five cycles visible on the screen). Observers were asked to report the shape of the surface, the number of visible cycles and whether a peak or a trough of the surface appeared just under the horizontal midline of the surface. This last judgement was required to ascertain whether the relative depth in the surface was accurately perceived. In many previous studies, although perceptions of depth had been elicited, the order of relative depth had been ambiguous and the same surface appeared as concave or convex on different occasions.

In the present experiment, the depth and number of cycles of the simulated surface was clearly perceived by all the observers. Some subjects did, however, sometimes have difficulty in distinguishing a sinusoidal from a triangular corrugation although this improved with practice. Secondly, the relative depth relationships within the surface were correctly perceived on all occasions. There was no ambiguity in the front/back depth relationship of the surfaces. This was true both for the active and passive parallax conditions. In the case of active parallax, observers perceived a trough or a peak depending on whether the movement of that part of the pattern was in the same direction as, or opposite to, the direction of translation of the observer. In the passive parallax situation a peak was perceived when that part of the surface moved in the same direction as the oscilloscope and a trough when it moved in the opposite direction.

This initial phenomenal investigation clearly showed that motion parallax, in isolation from other sources of depth information, could act as a powerful, effective source of information about the three-dimensional structure of depth surfaces. A further study went on to look at whether motion parallax could act as a quantitative as well as a qualitative source of information about depth. That is, whether the amount of relative movement between two parts of the pattern was lawfully related to the amount of perceived depth between them.

3.4 Matching depth from motion parallax with stereoscopic depth.

A stereoscopic matching task was used to measure the amount of depth perceived in parallax surfaces containing different amounts of relative motion. Observers were required to adjust the depth in a stereoscopic surface to match the perceived depth of the parallax surface. The experimental set-up used for this matching task is shown in Figure 3.5a. It consisted of a stereoscopic display positioned alongside the usual motion parallax display. In the stereo display two random dot patterns were presented on two oscilloscope screens. The two patterns were viewed independently by the two eyes by means of a mirror arrangement. Motion parallax, corrugated, depth surfaces

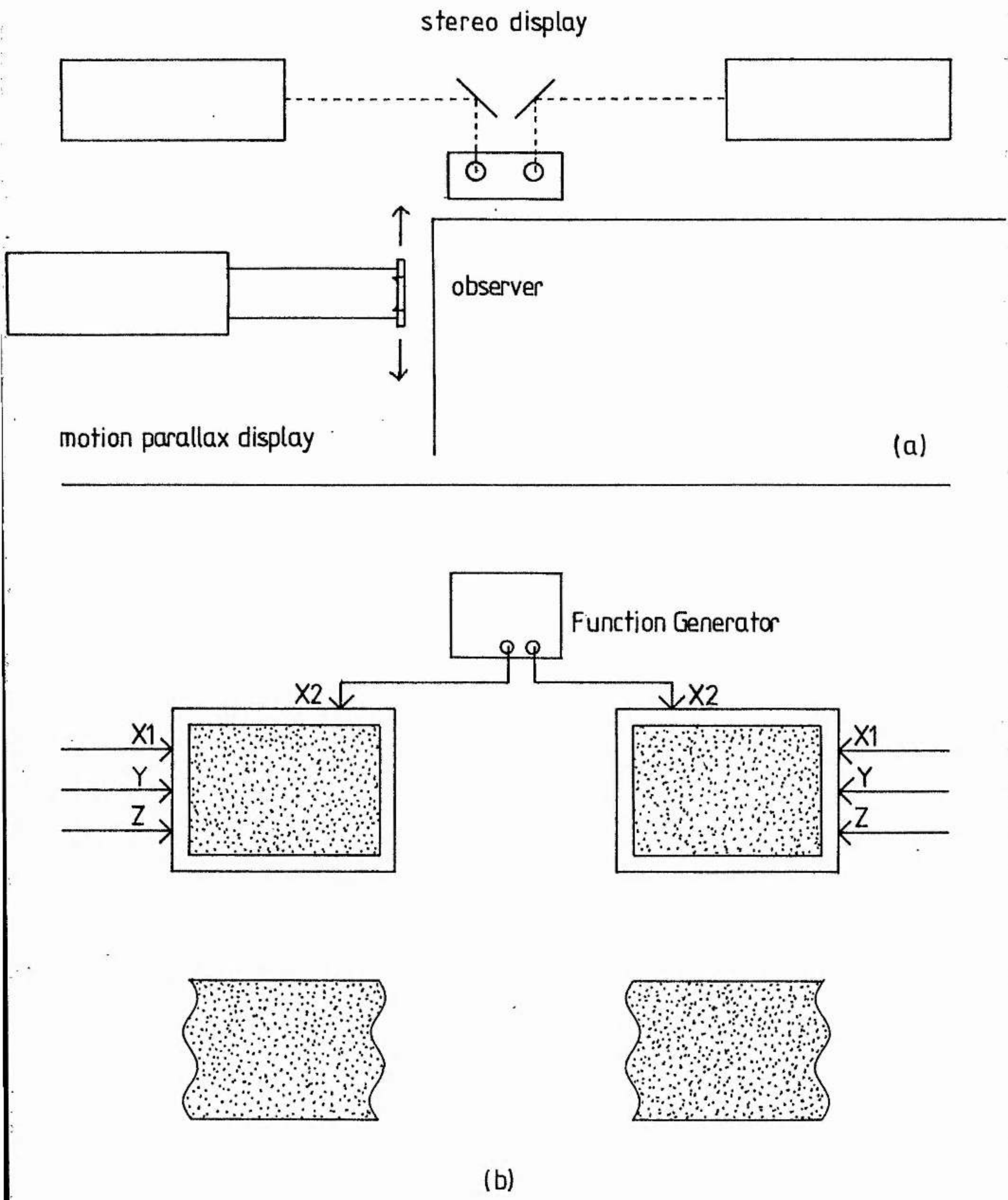


Figure 3.5.

(a) The experimental arrangement used for matching depth from motion parallax and stereoscopic depth. The observer viewed the parallax display while moving on the chinrest and then looked at the stereo display.
(b) In the stereo display, two random dot patterns, which were viewed independently by the two eyes, were distorted by a signal of the same shape but with opposite phase. This created disparities between the two patterns so that a depth surface was perceived when they were fused stereoscopically.

containing different amounts of peak-trough depth were simulated using patterns of relative motion as described earlier. In the stereoscopic display corrugated depth surfaces, of the same shape as those simulated in the parallax display, were produced by introducing binocular disparities between two random dot patterns. The horizontal disparities between the two patterns were created by adding a disparity signal of opposite phase to the X input of each scope. For example, adding a sine wave of opposite phase to each scope created disparities such that, when the two patterns were viewed stereoscopically, a sinusoidally corrugated depth surface was perceived (Figure 3.5b). The shape of the three-dimensional surface could be altered by changing the form of the disparity signal and the amount of perceived depth could be changed by varying the amplitude of this signal. In the present experiment, the disparity signal specified a corrugated surface of the same shape as that simulated in the parallax display. The amplitude of the disparity signal could be altered by the observer, so that the depth of the stereo surface could be adjusted to match the perceived depth of the parallax surface.

Observers were asked to make matches for simulated motion parallax surfaces of three different depths. Judgements were made for parallax surfaces viewed in both active and passive parallax conditions. For the three different depths, the amount of relative motion between a peak and a trough of the pattern was 0.7, 1.5 and 3.4 minutes of arc for each degree of head or scope movement. In each case the spatial frequency of the depth corrugation was set at 0.3 corrugation cycles per degree of visual angle. Observers viewed the parallax surface for several seconds, while moving from side to side on the chinrest in the active parallax situation, or while viewing the moving scope in the passive parallax situation. They then moved to the stereo display and adjusted the amplitude of the disparity signal until the perceived depth of the stereoscopic surface appeared to match the perceived depth of the parallax surface. Subjects were allowed to switch between the two displays several times until they were satisfied that the peak to trough depth was the same for both surfaces.

The results obtained in this initial matching experiment are shown in Figure 3.6a. The amount of physical disparity needed to match the perceived depth of the parallax surface increased as the amount of relative movement in the parallax transformation increased. This was true both in the active parallax condition and in the passive parallax situation, although the amount of perceived depth was a little less for the passive parallax condition. It is interesting to note that the perceived depth was less than that which would be predicted from theoretical calculations, particularly at large amplitudes (dotted lines in Figure 3.6a). This seems to be in accordance with the phenomenal impression that, at large amplitudes, the perceived depth reached an asymptotic level and relative movement was then noticed within the surface. That is, above a certain limit, the additional relative motion was no longer interpreted as an increased depth difference but was perceived as motion. Another factor which might have contributed to the discrepancy, was that correct matching depended on the accuracy with which relative depth based on disparity was perceived. Finally, the amount of depth perceived in a parallax surface depends on the distance of the display from the observer and the extent of translation. If these parameters were misperceived, the perceived depth would not have been equivalent to the predicted absolute depth.

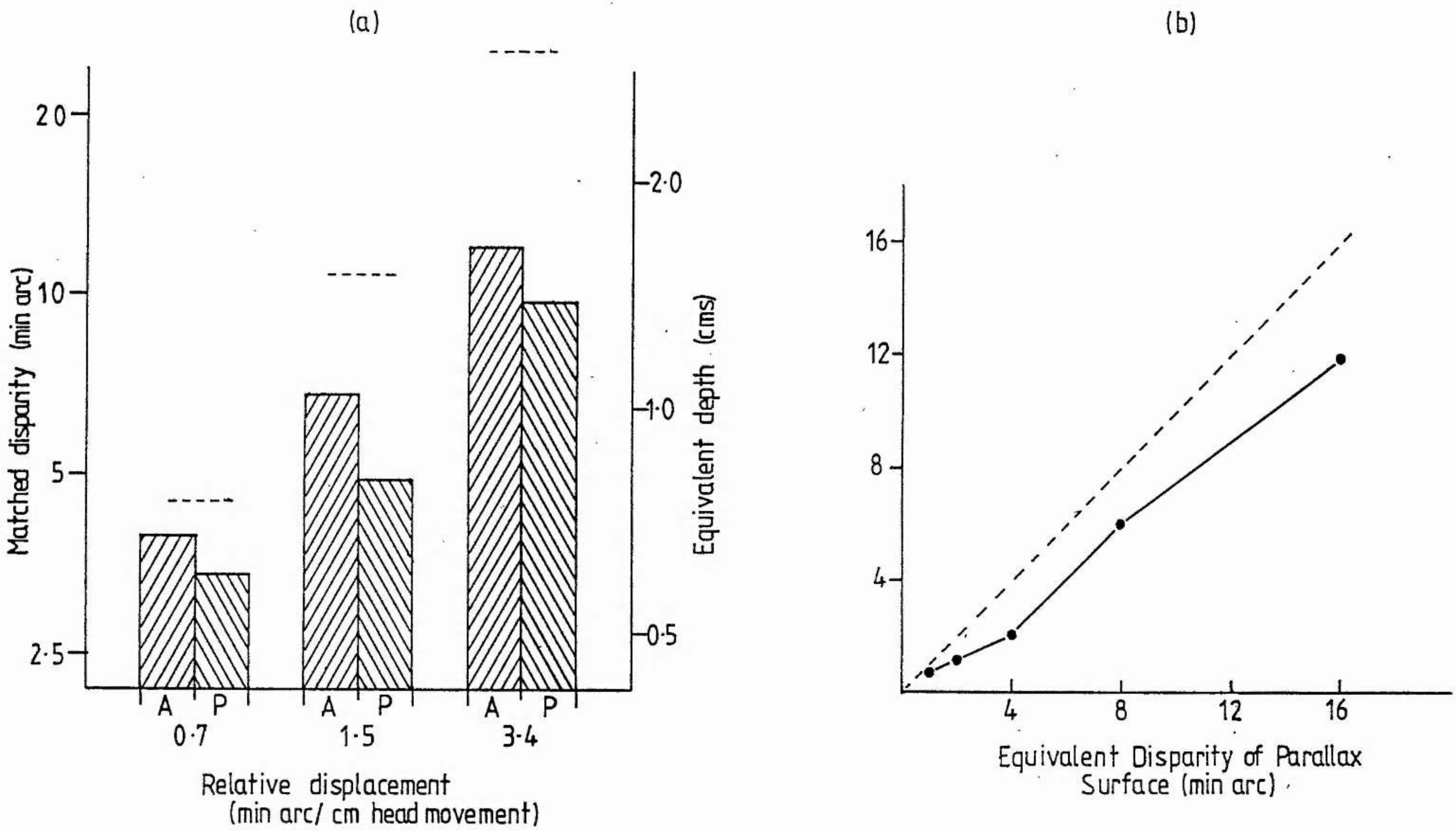


Figure 3.6. (a) The peak to trough disparity of the stereoscopic surface matched with parallax surfaces containing three different amounts of relative motion. Mean data for nine subjects is shown for both active (A) and passive (P) parallax situations. Dotted lines show expected match.
(b) Stereoscopic-parallax matching data for one observer (MEG) in a passive parallax situation.

Recent experiments designed to extend these original findings, have investigated stereo-parallax matching using a more sophisticated experimental arrangement for comparing stereo and parallax depth. This display is described in chapter 8. Parallax information was provided by introducing relative motion into a random pattern displayed on an oscilloscope which swung from side to side across the observers line of sight. Figure 3.6b shows that in this passive parallax situation, stereo and parallax depth could be successfully matched but again the matched disparity was less than the equivalent disparity of the parallax surface.

3.5 Discussion and further informal observations.

The initial experimental observations demonstrated clearly that motion parallax was a sufficient and effective cue for the shape and depth of three-dimensional surfaces. Not only was the phenomenal impression of depth striking, but the amount of perceived depth in the surface related monotonically to the amount of relative movement in the display. The perceived depth surface was completely unambiguous and was perceived as a rigid three-dimensional surface containing no relative motion. This was true both in an active parallax situation, which simulated the relative motion transformations produced during active movement of the observer, and in a passive parallax situation which simulated movement of a three-dimensional object across the line of sight of a stationary observer.

The actual extent and velocity of head movement in the active parallax situation did not seem to be crucial for the perception of the depth effects. Indeed observers varied considerably in their preferred speed for viewing the parallax display. However, these parameters were not systematically investigated. Previous work by Hell (1978), reported in the last chapter, suggests that motion parallax reaches an asymptotic effectiveness at head velocities above 6cms/sec, and the velocities used here were well above this limit. Another factor which might potentially have been crucial to the reported depth effects was the density of the random dot pattern which carried the relative motion transformation. Due to the use of slightly different displays, densities were in fact varied by a factor of four over a series of different experiments and this did not alter the nature of the depth effects. The lowest density used was, however, not less than six texture elements per degree. Some preliminary observations on the effect of drastically reducing the number of dots are reported in the following chapter.

In the observations described so far, the subject viewed the transforming random dot pattern monocularly. It is interesting to also investigate how the perception of parallax surfaces alters when they are viewed binocularly. In this situation conflicting stereoscopic information indicates that the surface is flat. It was found that when observers viewed the parallax display binocularly, they typically reported that the pattern was still perceived as a three-dimensional depth surface but that relative motion was perceived within the surface and this made it appear to twist or deform. The percept was rather similar to that observed for very high amplitudes of relative motion when the depth effect started to break down. However, it was clear that the perception of parallax depth was not destroyed by the presence of conflicting stereoscopic information.

Finally, in light of the equivocal results obtained in earlier studies, observers were also asked to look at a stimulus situation which was more similar to those used in some of these earlier studies (eg. Braunstein, 1976; Farber and McConkie, 1979). It was found that, in the present study, the consistent, unambiguous depth effects found for parallax depth depended crucially on the linkage between the relative movement of different parts of the pattern and the translatory movement of the observer or the oscilloscope. When this linkage was taken away so that both observer and scope remained stationary, but an equivalent pattern of relative motion was still introduced into the random dot pattern, then the depth effects became ambiguous. In most cases, observers still reported perceiving a depth surface but the front/back relationships within the surface were not consistently perceived, so that, an identical part of the pattern appeared concave or convex at different times and these interpretations often reversed spontaneously. This depth ambiguity is similar to that found in the Kinetic Depth Effect, and indeed in this situation the stimulus appeared very like a KDE stimulus since the surface appeared to rotate about an axis in the centre of the screen. Often, some deformation was also observed within the surface. The crucial factor in determining whether a parallax surface will be perceived unambiguously seems to be whether the overall direction of translation of the surface with respect to the observer can be determined. When the relative motion is not linked to head or scope movement the parallax information simulates a surface passing behind an aperture and such a situation has been common in earlier studies (Braunstein 1976). This situation does not seem to allow the overall translation of the pattern to be unequivocally perceived except under certain conditions (Braunstein and Andersen, 1981). In contrast, when the relative movement transformation is linked to the movement of the observer or the scope, the translatory component of motion can easily be determined from the relative displacement of the scope with respect to the rest of the visual field. In the case of active parallax, of course, additional information from non-visual sources can also provide information about the extent and direction of head movement. This might be one reason for the slightly larger perceived depths found for the active parallax condition in the present matching experiment.

In summary, the initial experiments on the perception of depth from motion parallax demonstrated that parallax can act as an effective cue to the shape and depth of three-dimensional surfaces in isolation from other sources of depth information (Rogers and Graham, 1979). The technique used for generating parallax depth surfaces was flexible enough to allow further investigation of parallax processing. The rest of this thesis describes experiments which were designed to determine the parameters of the motion parallax depth system in detail and to indicate the type of mechanisms which might be involved in processing parallax information.

Chapter 4 The Sensitivity of the Motion Parallax Depth Processing System

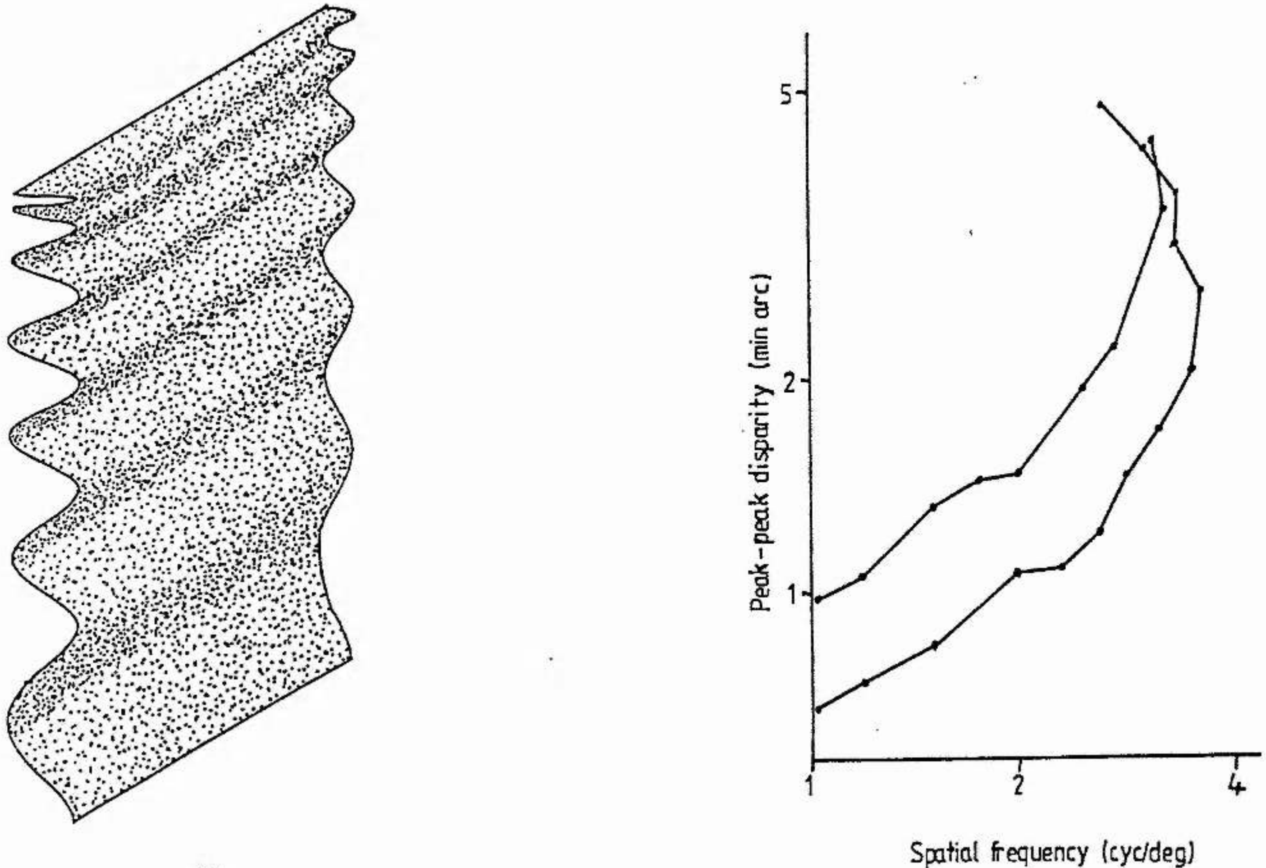
4.1 Introduction.

The experiments described in the previous chapter demonstrated that motion parallax can act as a powerful, accurate source of information about the structure of three-dimensional objects and surfaces. The experiments described in this and subsequent chapters were designed to investigate the way in which depth information from motion parallax is processed by the visual system. That is, to determine the underlying characteristics of the motion parallax processing system.

An initial requirement, was to determine the limiting conditions for the effective use of motion parallax information. This was done by measuring the visual system's sensitivity for detecting small depth modulations in surfaces specified by parallax information. The minimum amount of relative movement that was needed to detect that a surface was corrugated in depth, rather than flat, was taken as a measure of the threshold for depth perception. By measuring this threshold as a function of the spatial frequency of the depth surface, a sensitivity function was determined which provided a good characterisation of the properties of the processing system. In the luminance domain, the analogous contrast sensitivity function, derived from thresholds for detecting the presence of luminance gratings of different spatial frequencies, has proved very useful in characterising the properties of luminance processing within the visual system (Campbell and Robson, 1968).

In an earlier study, Tyler (1974) measured depth thresholds for detecting stereoscopic corrugations, where the depth was specified by binocular disparity. A random dot stereogram was used to portray a surface which was corrugated in depth, such that, the spatial frequency of the corrugation decreased from the top to the bottom of the pattern, and the peak to trough depth in the corrugation decreased from the left to the right of the pattern (Figure 4.1a). Observers were asked to mark a line on the surface which represented the point at which the depth in the corrugation appeared to fade out and the surface appeared to be flat. This line gives a rough measure of the threshold depth amplitude needed to detect a depth corrugation for different spatial frequencies.

As shown in Figure 4.1b, Tyler found that as the spatial frequency of the depth corrugation increased from one cyc/deg., the peak to trough depth needed to detect the presence of a corrugation increased gradually until, at about 4 cyc/deg, and above, it was no longer possible to perceive a corrugated depth surface at any amplitude. This point, therefore, reflects the resolution limit for detecting stereoscopic depth corrugations. The characteristics of stereoscopic depth sensitivity for spatial frequencies below 1 cyc/deg, was not determined in this study. A wider range of frequencies was, however, investigated in a related study which looked at the ability to detect the presence of a sinusoidal depth wiggle in a stereoscopic, vertical line (Tyler, 1975a). Here, a fall-off in sensitivity similar to that found for textured surfaces, occurred for depth spatial frequencies



(a)

(b)

Figure 4.1.

(a) The corrugated depth surface used by Tyler (1974) to measure sensitivity to depth corrugation. The surface decreases in corrugation frequency from top to bottom and decreases in peak to trough depth amplitude from left to right.
(b) The sensitivity function obtained by Tyler (1974) for two observers. The peak to trough disparity at detection threshold is shown as a function of corrugation spatial frequency.

above 1 cyc/deg. For frequencies below 1cyc/deg, there was a peak in the sensitivity function between 0.3 and 1 cyc/deg with sensitivity decreasing substantially below this point. In this study, Tyler also measured the upper depth limit, that is, the maximum disparity for which depth could still be perceived. For line stimuli, this limit decreased linearly as the spatial frequency of the depth modulation increased. The lower and upper limits for perceiving depth, measured in this study, suggest that there are strict spatial limits within which the disparity processing mechanism of the human visual system can operate.

Although Tyler had investigated stereoscopic depth sensitivity, there had previously been no attempt to characterise the motion parallax depth processing system in similar terms. The development of the technique described in the last chapter, made it possible to measure thresholds for parallax depth surfaces as well as stereoscopic surfaces. Detection thresholds were, therefore, measured for corrugated depth surfaces where the depth was specified by patterns of relative motion, rather than disparity. Sinusoidal depth corrugations were simulated by introducing the appropriate pattern of relative motion into a random dot pattern, as described previously. Threshold was defined as the minimum amount of relative movement between the part of the pattern corresponding to a peak and the part corresponding to a trough, that was needed for depth modulation to be detected. This threshold was measured for simulated sinusoidal corrugations which varied over a range of spatial frequencies.

To allow the characteristics of parallax sensitivity to be legitimately compared with those for stereoscopic depth, sensitivity functions were also determined for corrugated depth surfaces specified by binocular disparities. Thresholds for detecting stereoscopic corrugations were measured using identical display characteristics and psychophysical procedures to those used for parallax surfaces. This part of the experiment was an extension of Tyler's initial study of sensitivity to stereoscopic depth corrugations (Tyler, 1974).

4.2 Methods.

i) Motion parallax surfaces

Motion parallax information specifying sinusoidally corrugated surfaces was produced in the general way described in the last chapter, but using a more sophisticated experimental arrangement (Figure 4.2). As before, observers viewed, monocularly, a two-dimensional random dot pattern on an oscilloscope, as they moved from side to side on a chinrest. As the observer moved, the pattern was systematically transformed in such a way as to simulate the motion parallax information that is provided as an observer moves laterally while viewing a real three-dimensional surface. For the present experiment the simulated surface was a sinusoidally corrugated surface of varying spatial frequency and peak to trough depth (amplitude). The details of stimulus generation are shown in Figure 4.2. The random dot pattern was displayed on a Hewlett Packard large screen oscilloscope (HP1304A) located 57cms. from the observers eyes, so that, the screen subtended 25deg (horizontally) by 20deg (vertically) of visual angle. The random dot pattern was generated using a Matrox ALT 256 graphics board which was loaded using a Cromemco System III computer. The graphics board produced an array of 256 by 256 points and these were randomly set to

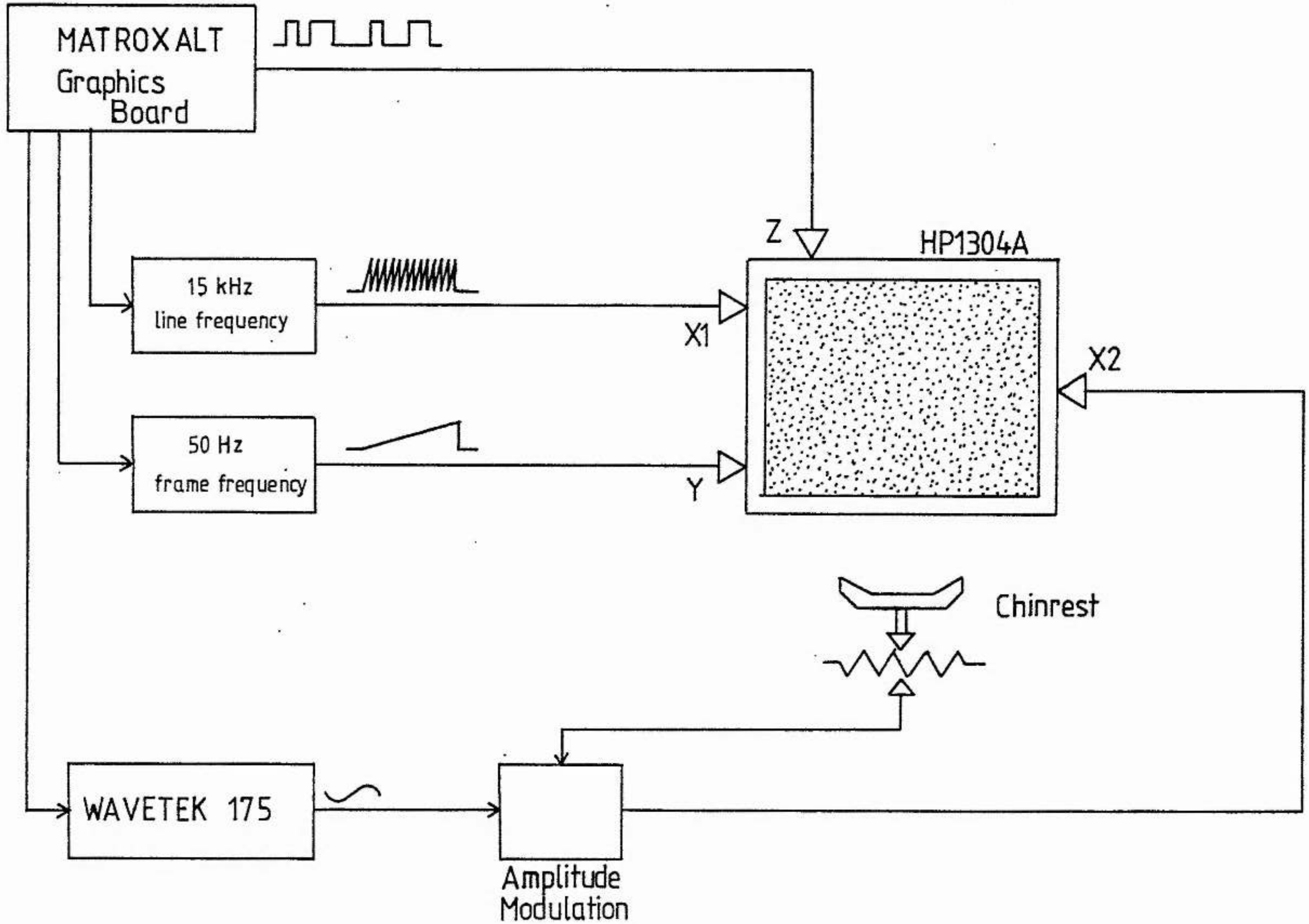


Figure 4.2.

The motion parallax display: A 256x256 random dot pattern is displayed on an oscilloscope using a raster technique. The Matrox graphics board provides the Z intensity signal and the sync pulses for the line and frame ramp generators. The entire pattern can be distorted by an additional input (X2) whose amplitude is controlled by the position of the observer's head on the chinrest.

light or dark with a 50% probability. The pattern was displayed on the oscilloscope screen using a raster scan, where the X and Y deflection signals were triggered by line and frame sync pulses from the graphics board. The display was refreshed at a rate of 50Hz.

The parallax or distortion signal, which produced the relative motion transformation of the pattern, was generated using a Wavetek 175 arbitrary waveform generator, which was synchronised to the frame rate of the display. In the present experiment this signal was a sinusoidal waveform of variable frequency and amplitude. The amplitude of this signal was also continuously modulated by a voltage derived from a potentiometer which monitored the position of the chinrest. In this way, the relative motion transformation was linked to the movement of the observer such that when the observer remained stationary there was no relative movement. The display therefore simulated the parallax information which is produced by a real three-dimensional surface when it is viewed during lateral movement. As reported in the last chapter, when observers viewed the transforming random dot pattern while moving from side to side, they perceived a solid three-dimensional surface which appeared corrugated in depth. The relative motion within the pattern was not perceived. The frequency and overall amplitude of the parallax signal determined the perceived spatial frequency and peak to trough depth of the depth corrugation.

ii) Stereoscopic surfaces

In order to compare sensitivity for depth from motion parallax to that for stereoscopic depth, the apparatus shown in Figure 4.3 was used to display stereoscopic surfaces. The stereo surfaces were identical

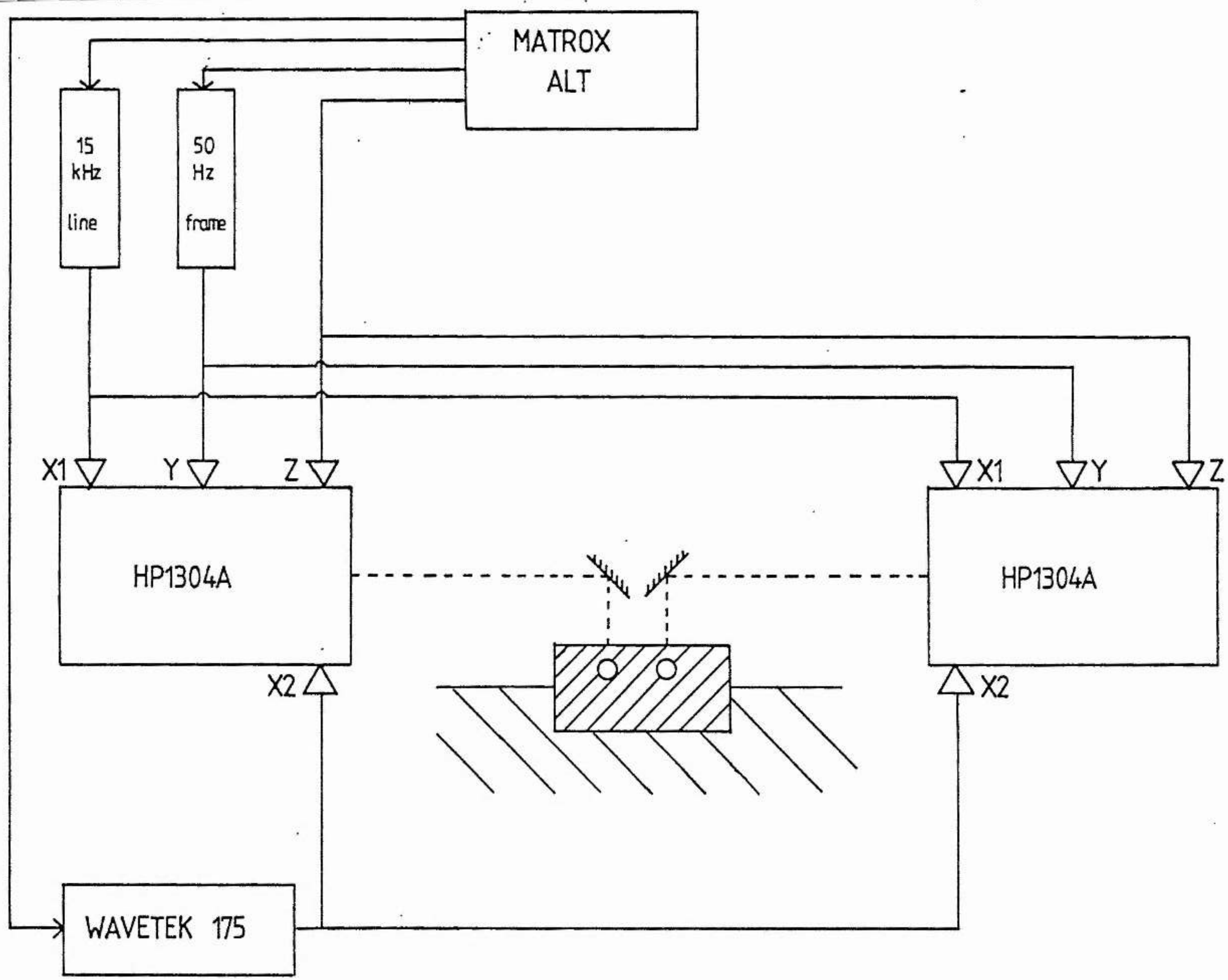


Figure 4.3. The stereoscopic display: Two identical random dot patterns were displayed using a raster technique. An additional signal was fed to one of the scopes and the same signal with inverted phase was fed to the other scope. This created disparities between the two patterns which were viewed independently by the two eyes.

to those produced in the motion parallax display, except that the depth information was given by binocular disparity rather than relative motion.

The stereoscopic display consisted of two Hewlett-Packard 1304A display scopes which were viewed stereoscopically through a pair of mirrors in front of the observer's eyes and at 45 degrees to the line of sight. The scopes were positioned 57cms from the observer's eyes and subtended 25deg (horizontally) by 20deg (vertically). Identical random dot patterns were displayed on the two screens and consisted of an array of 256 by 256 points which were randomly bright or dark. The angular subtense and the overall dot density of the pattern was therefore identical to that used in the parallax display. When viewed stereoscopically, these two patterns were fused and were seen as a single flat two-dimensional random dot pattern in the plane of the oscilloscope screen. A sinusoidally corrugated depth surface was produced by introducing a horizontal shift or disparity between the rows of the two patterns, where the extent of the shift varied sinusoidally from the top to the bottom of the pattern. To do this, a sine wave signal from the Wavetek 175 was fed to each of the two scopes, with the phase of the signal being opposite for each scope. This created the appropriate disparities between the patterns on the two scopes, so that, when they were fused, a single, three-dimensional corrugated surface was perceived. By changing the frequency and amplitude of the disparity signal, the spatial frequency and the peak to trough depth of the perceived corrugation could be varied. It was therefore possible to simulate identical depth surfaces in both the parallax and stereo displays.

iii) Procedure

The same psychophysical procedures were used to measure thresholds for perceiving both parallax and stereo corrugated surfaces. An ascending method of limits was used in both cases. The amplitude of the peak to trough depth in the corrugated surface was increased gradually until the observer could just perceive that a corrugated depth surface was present. This was done by increasing the gain of the distortion signal for the parallax display, or the amplitude of the disparity signal for the stereoscopic display. This had the effect of increasing the overall amount of relative movement, or disparity, present in the display. The observer was required to press a key as soon as a corrugated depth surface could be perceived, and was asked to report, verbally, the number and phase of the corrugation cycles that were perceived in the depth surface. This rather conservative criterion was used to ensure that observers were making their judgements on the basis of perceived depth and not, for example, on the detection of relative movement or displacement.

Motion parallax and stereoscopic thresholds were measured on separate days, for three observers. For the motion parallax display, observers viewed the stimulus monocularly while moving from side to side on the chinrest, while for the stereo display, observers remained stationary and viewed the fused pattern binocularly. Each experimental session consisted of 48 trials comprising eight repetitions of six different spatial frequencies presented in random order. On each trial the amplitude of the depth corrugation was increased in 10% (0.82dB) steps, from a value around six to eight steps below the previous threshold setting, at a rate of one step every second. When the observer could just perceive the depth modulation, a keypress terminated the trial and the amplitude of the corrugation was reset to zero, so that only a flat random dot surface was present on the screen. The amount of overall relative movement, or disparity, that was present within the depth surface at the time of the keypress was recorded as the threshold measure for each trial.

4.3 Results.

The measured sensitivity functions for perceiving depth from motion parallax information are plotted in Figure 4.4 for the three subjects. Each data point shows, for each spatial frequency, the average amount of peak to trough relative motion within the surface at the point where depth could just be perceived. The threshold is expressed as the amount of relative displacement, in sec arc, between a row in the pattern corresponding to a peak and a row corresponding to a trough, produced by each centimetre of observer movement. On the abscissa, the spatial frequency of the perceived corrugation is plotted in cycles per degree of visual angle.

The shape of the observed sensitivity function was very similar for all three observers. As shown in Figure 4.4, the peak sensitivity for detecting corrugated surfaces occured when the spatial frequency of the surface was between 0.2 and 0.4 cyc/deg. Sensitivity decreased at both higher and lower spatial frequencies. For two subjects, in the region of peak sensitivity, the amount of peak to trough relative motion needed to perceive depth modulation was only 6sec arc for each centimetre of head movement. The ability to perceive depth with this

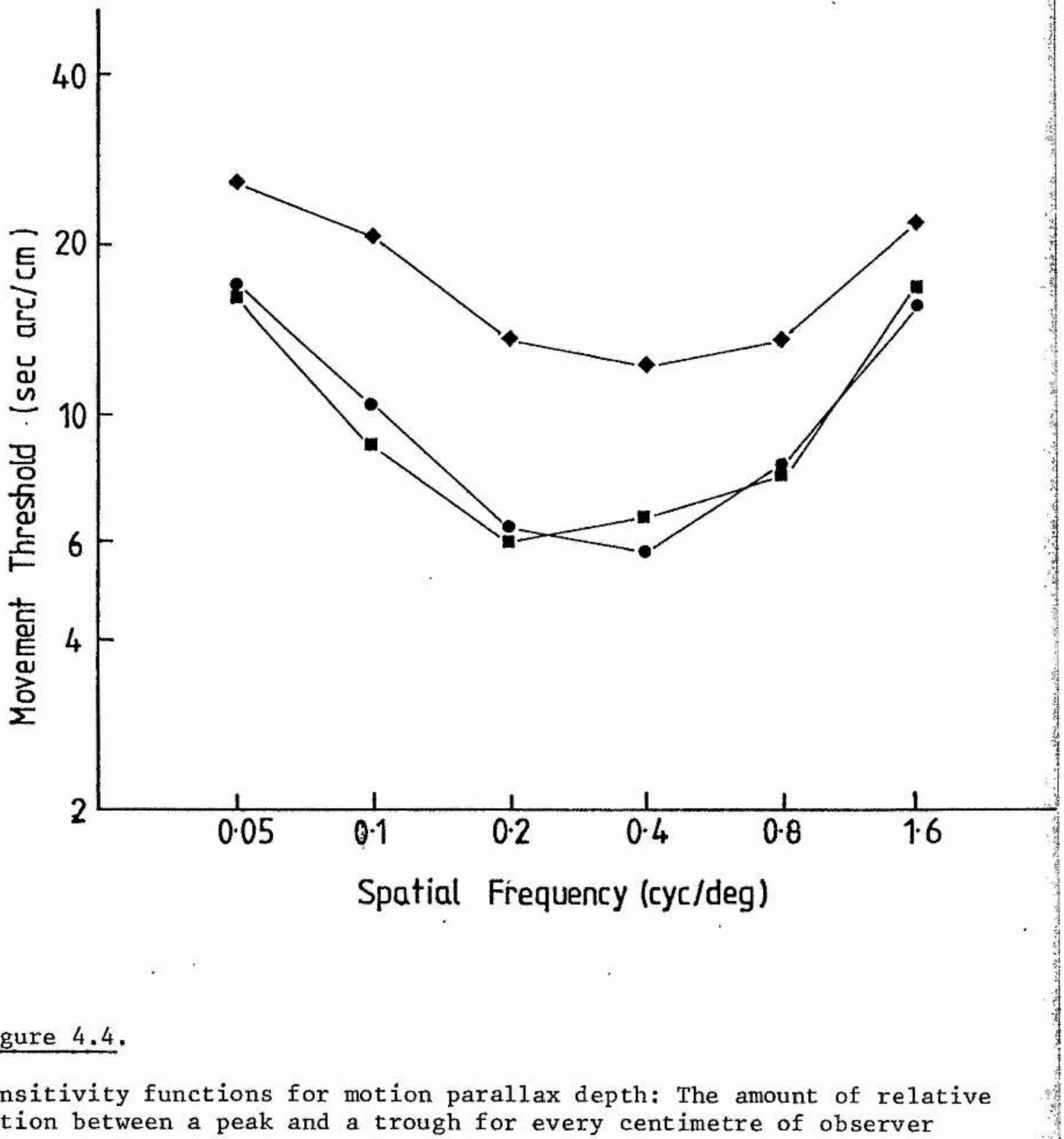


Figure 4.4.

Sensitivity functions for motion parallax depth: The amount of relative motion between a peak and a trough for every centimetre of observer movement, needed to detect the presence of a depth corrugation was measured as a function of the spatial frequency of the depth corrugation. The data are shown for three observers, BJR (■), MFG (●), and JGQ (◆).

amount of relative motion is equivalent to being able, on the basis of parallax information, to detect that a real three-dimensional surface is corrugated when there is a difference in depth of only 1mm between the peak and the trough of the surface. Although the sensitivity for parallax depth is reduced by a factor of two for the third subject this still represents a high sensitivity to depth modulation.

The sensitivity functions obtained for detecting corrugated depth surfaces where the depth was specified by binocular disparity, rather than relative motion, are shown in Figure 4.5. The amount of disparity between a peak and a trough row at threshold is expressed, in sec arc, as a function of the spatial frequency of the depth corrugation in cycles per degree. Peak sensitivity occured at between 0.2 and 0.4 cyc/deg and decreased at higher and lower spatial frequencies. In absolute terms, peak sensitivity was as low as 20 sec arc peak to trough disparity difference, and such a value compares well with measures of stereo sensitivity found in other studies (Tyler, 1974, 1975; Schumer and Ganz, 1979). This level of sensitivity corresponds to being able to perceive the depth in a real three-dimensional corrugation when the peak to trough depth difference, over about three degrees of visual angle, is only 0.5mm.

The level of sensitivity found in this experiment for detecting depth modulation in both parallax and stereoscopic surfaces compares well with the early threshold data measured by Tschermak-Seysenegg (1939). She found that two wires were perceived to lie at different depths when the physical depth difference between them was 0.8mm for monocular and 0.5mm for binocular viewing. The viewing distance was however less than that used here and hence the angular thresholds are

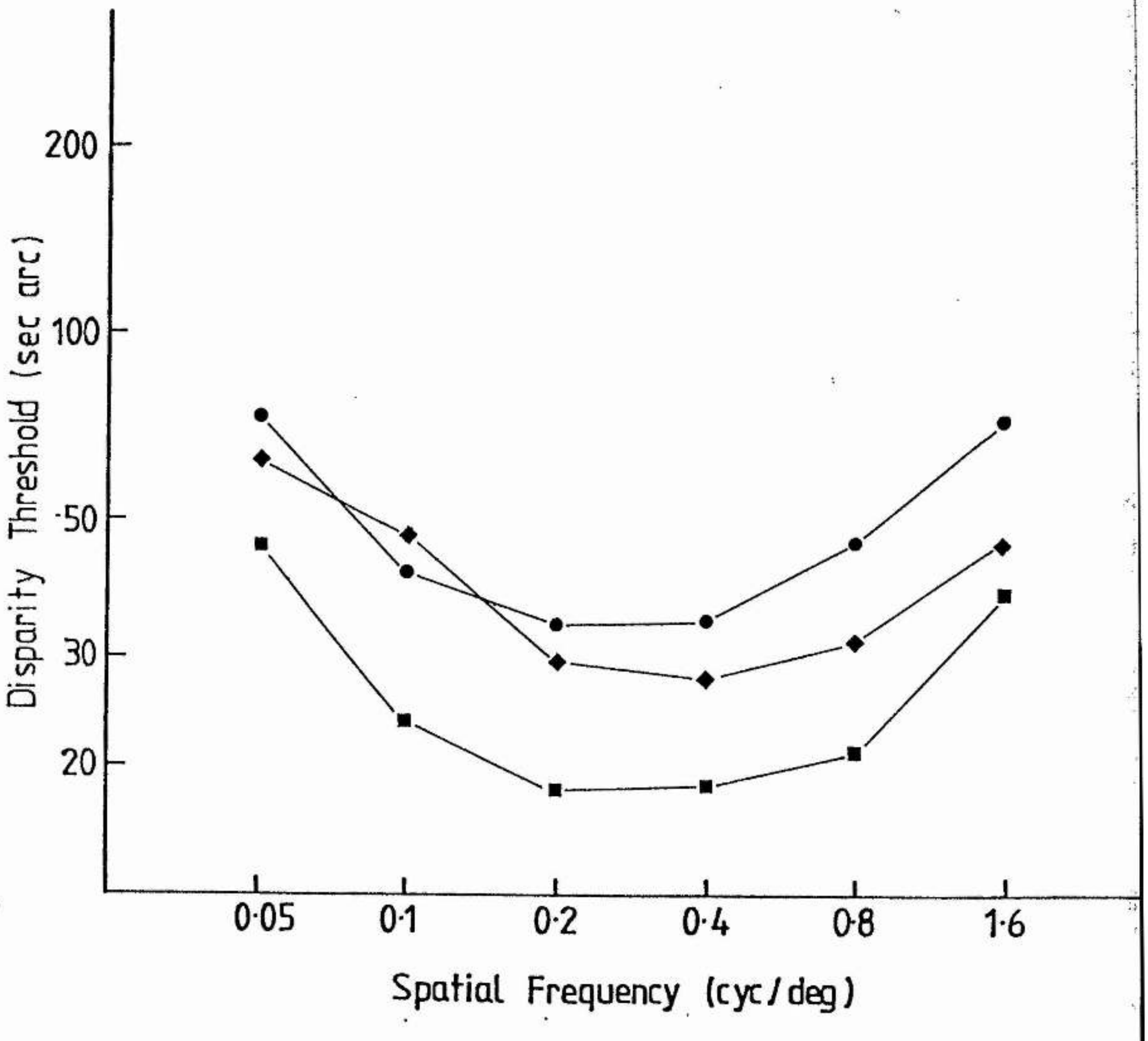
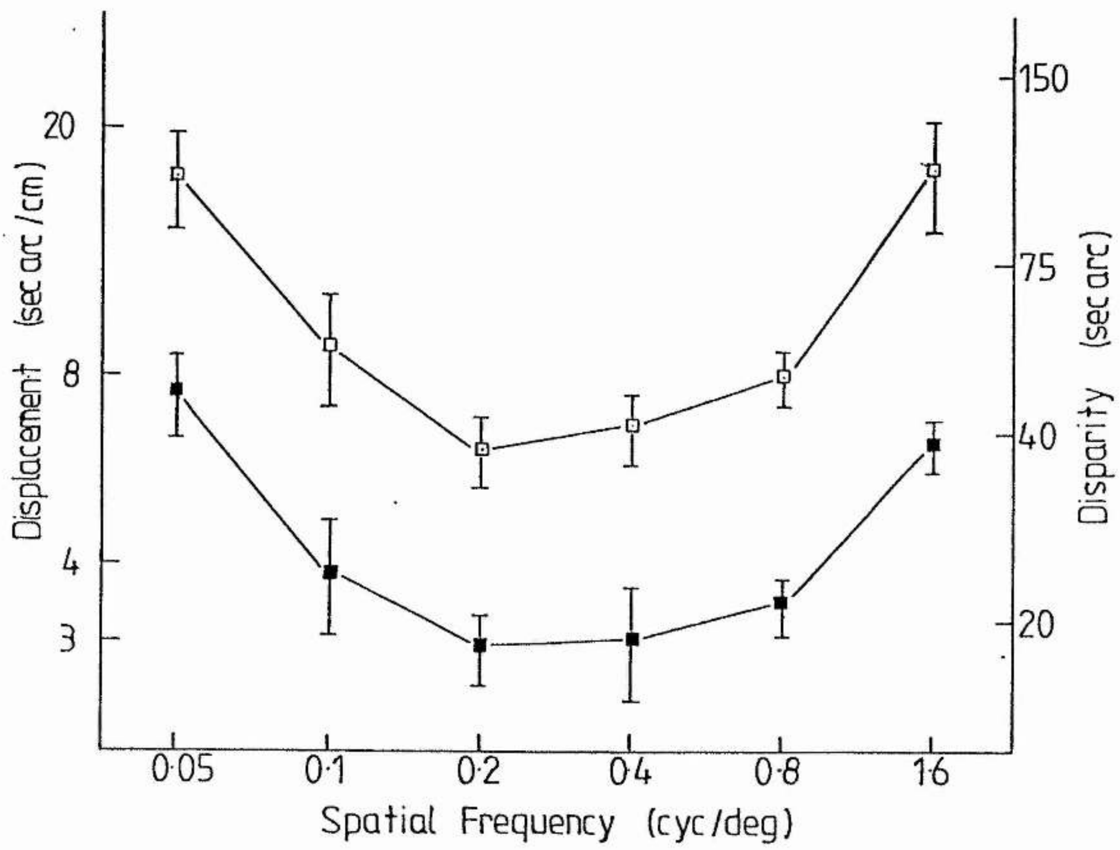


Figure 4.5.

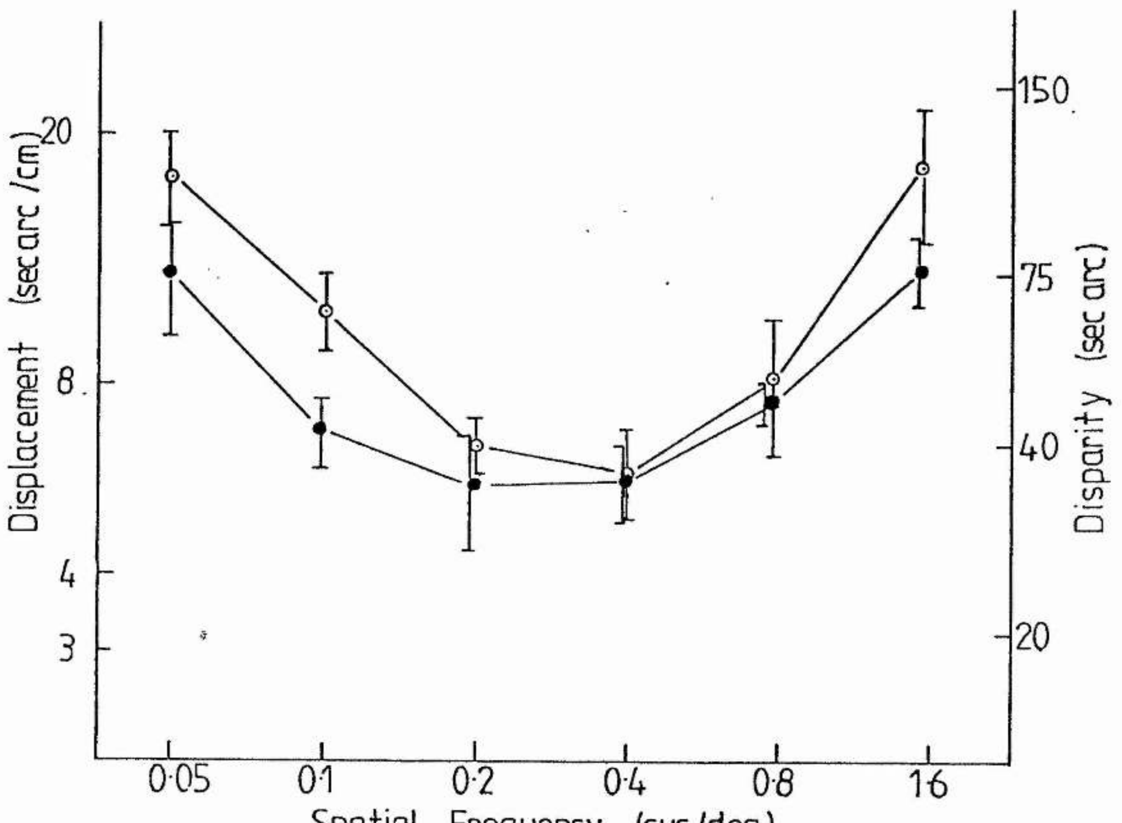
Sensitivity functions for stereoscopic depth: The amount of peak to trough disparity that was needed to detect the presence of a depth corrugation was measured as a function of the spatial frequency of the corrugation. The data are shown for three observers, BJR (■), MEG (●), and JGQ (◆).

slightly higher.

One immediately striking feature of the two sets of data, is the close similarity between the sensitivity functions for motion parallax and stereoscopic depth. To make this similarity clearer, the data have been replotted in Figure 4.6, to show the parallax and stereo thresholds together for each observer. For all observers the shape of the function is remarkably similar in both cases, with peak sensitivity occurring at the same spatial frequency and falling off at either side of this frequency. In this figure the parallax and stereo data have been plotted using the same ordinate so that the absolute sensitivity to depth for each system can be directly compared. This is possible because the depth of a parallax surface, besides being expressed as relative motion per degree of head movement, can also be expressed as the disparity of the real three-dimensional surface simulated by using this amount of relative movement. Intuitively, for a real three-dimensional surface, it is possible to calculate both the amount of peak to trough relative parallax produced by the surface for a given extent of head movement, and the binocular disparity caused by the peak to trough depth difference. Hence, it is straightforward to transform one measure into the other. In fact, in the special case of lateral movement through a distance equivalent to the interocular distance, the cumulative peak to trough relative movement has the same value as the binocular disparity of the surface. As a result of this relationship, it is possible to transform threshold data for motion parallax surfaces into units of <u>equivalent disparity</u>, so that a direct comparison can be made with data for stereoscopic surfaces. When the data are plotted in this way (Figure 4.6) it can be seen that the absolute sensitivity for motion parallax and stereoscopic depth differed by about a factor of

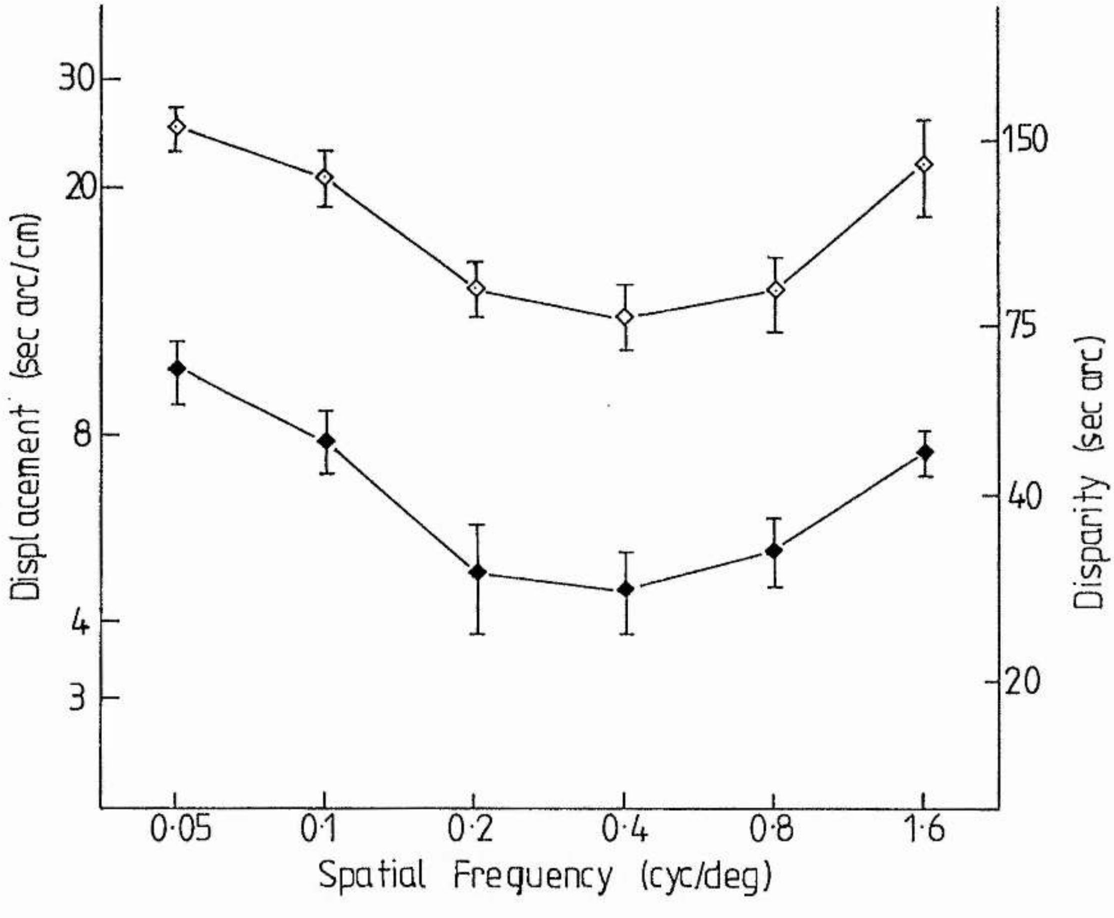


(a)



(b)

(Figure 4.6. - see over)



(c)

Figure 4.6.

The sensitivity functions shown in Figures 4.4 and 4.5 replotted to allow the parallax and stereoscopic depth sensitivities to be compared for each of the observers. The data are shown for BJR (a), MEG (b) and JGQ (c).

two for two of the three observers. Observer BJR (Figure 4.6a), for example, showed a peak sensitivity for stereoscopic surfaces of around 20 sec arc of disparity, while for parallax, peak sensitivity was around 40 sec arc of equivalent disparity. For observer MEG (Figure 4.6b) the absolute sensitivity of both systems was very similar.

4.4 Discussion.

i) Absolute sensitivity of the motion parallax system

The sensitivity functions for perceiving corrugated depth surfaces specified by motion parallax information, show that the visual system can use very small relative displacements between parts of a textured surface to obtain information about the relative depth within that surface (Rogers and Graham, 1982a). At the point of maximum sensitivity a displacement of only 6 sec. arc for each centimentre of head movement was needed to perceive depth, and this displacement occured between rows of the pattern which were two to four degrees apart. This represents a very high acuity for depth modulation and suggests that depth from relative motion is yet another sensory dimension for which the visual system shows hyperacuity. As mentioned above, this sensitivity corresponds well to that observed for detecting a depth difference between two wires. This suggests that the early threshold studies, described in chapter 2, were in fact measuring a true depth threshold rather than a differential velocity or vernier alignment threshold. The data also demonstrate that the ability to use relative motion to obtain depth information, extends over at least a five octave range of spatial frequencies. It seems, therefore, that motion parallax can be an effective source of depth information which is suitable for picking up very small depth modulations in three-dimensional surfaces.

Sensitivity to parallax information seems to vary by a factor of two or three between individual subjects. This has been borne out by the measurement of depth thresholds with large numbers of observers in laboratory classes. While some of this variation undoubtedly reflects criterion differences, it has been found that, with prolonged practice at observing the parallax surfaces produced in these experiments, the sensitivity function shows a substantial increase. In some sense, therefore, a learning process occurs as the observer becomes more familiar with this type of stimulus and this may be similar to the perceptual learning that occurs in perceiving random dot stereograms (Julesz, 1971).

The ability to use motion parallax effectively to gain information about the three-dimensional structure of a surface, clearly depends on the ability to detect the relative motion between the images of different texture elements belonging to the surface. The question, therefore, arises as to how the depth thresholds measured in the present experiment relate to the visual systems sensitivity to relative motion. A priori, it might be the case that depth thresholds are somewhat higher due to the extra processing involved in extracting the depth information from the motion. Phenomenologically, observers reported that in the present experiment there was no perception of relative movement in the stimulus either before, during or after the depth threshold has been reached. However, it was found informally that, when the spatial frequency of the corrugation was increased above the range measured here (ie. above 1.6 cyc./deg.), the depth effect began to break down and relative movement was perceived within the surface. So it seems possible that at higher frequencies where no depth threshold can be measured, a threshold for differential movement could be measured.

Much of the data on relative movement thresholds has been carried out with stimuli containing only a couple of lines or points (Gibson et al., 1957; Brandalise and Gottsdanker, 1959; McKee, 1981). These studies, therefore do not provide an adequate comparison for the present stimuli. However, a study which has looked at thresholds for differential movement in random dot patterns, and which has used stimuli very similar to those used here, was recently carried out by Nakayama and Tyler (1981a). They used high density random dot patterns, which contained relative motion, such that each row oscillated from side to side and the amplitude of the oscillation varied sinusoidally from the top to the bottom of the pattern. The stimuli were therefore similar to the parallax stimuli used here but the relative motion was not linked to the movement of the observer (who remained stationary throughout the experiment). Nakayama and Tyler report that the stimuli were perceived as patterns of relative motion and not as three-dimensional depth surfaces. The threshold measure was the minimum oscillation amplitude that was needed to detect movement in the random dot pattern. They measured thresholds for patterns with sinusoidal velocity gradients of different spatial frequencies and for oscillations of different temporal frequencies. They found that for an oscillation frequency of 2Hz the amplitude of the oscillation had to be only 5 arc sec for movement to be perceived in the pattern. This very high sensitivity was found for velocity patterns with a spatial repetition frequency of 3 cycles per degree which is well above the range of measured frequencies for parallax surfaces in the present study. Moreover, even at this spatial frequency, sensitivity decreased rapidly for lower and higher temporal frequencies, so that at 0.5Hz the threshold oscillation amplitude was around 40 sec arc. This temporal frequency is roughly equivalent to that of the head movements made in the present experiment. Nakayama and Tyler only measured thresholds at lower spatial frequencies when the temporal frequency was relatively high and so a direct comparison of the differential motion and the parallax depth thresholds is not possible.

When viewing parallax depth surfaces, observers found that, within the spatial and temporal limits normally used, it was not possible to perceive relative motion without also perceiving depth in the surface. This was true even when the relative motion was not linked to head movement so that the situation was similar to that used by Nakayama and Tyler. In this case, depth was perceived in the surface although the direction of the depth difference was ambiguous. It seems, therefore, that within the spatial and temporal limits used to measure thresholds for parallax surfaces, a meaningful separation of relative movement and depth thresholds cannot be made. Finally, however, informal observations suggest that at higher spatial and temporal frequencies depth percepts do break down and relative motion is perceived within the surface. The temporal and spatial limits found informally for parallax, seem to agree with those found for the Kinetic Depth Effect. For example, Caelli (1979,1981) has shown that, for shadows of rotating three-dimensional objects, the depth effect was lost when the temporal frequency of the rotation was increased above 2Hz. Above this limit, two-dimensional oscillations were perceived.

ii) Sensitivity for stereoscopic surfaces

The sensitivity functions measured for corrugated surfaces where the depth was specified by binocular disparities, were very similar to those found for parallax surfaces. Both the range of corrugation frequencies to which the system was sensitive, and the region of maximum sensitivity were similar for the two sources of depth information. In the case of stereoscopic vision, the sensitivity function for detecting depth in corrugated surfaces depends on being able to detect small differences in disparity between different areas of the random dot pattern. That is, the task involves picking up relative disparity between points separated in space. For some observers, in the region of peak sensitivity, a difference in disparity of only 20 sec. arc could just be detected between two areas which were two to four degrees apart. Again, the absolute sensitivity varied between individual subjects and this reflects the general wide variation in individual stereoscopic ability (Richards, 1970; Julesz, 1971).

The high acuity for detecting stereoscopic depth modulation, found in the present experiment, is consistent with the findings of Tyler (1974, 1975a) and Schumer and Ganz (1979). When Tyler (1975a) measured thresholds for detecting sinusoidal depth modulations in single lines, he found that peak sensitivity occurred at a spatial frequency of about 0.5 cyc/deg and ranged from 15 to 50 sec arc for different subjects. For corrugated depth surfaces the function was not measured below

1cyc/deg but, above this frequency, there was a decrease in sensitivity similar to that found here (Tyler, 1974). In a study by Schumer and Ganz (1979) thresholds were measured for stereoscopic corrugated surfaces which were produced using dynamic noise stereograms. A forced choice procedure was used and peak sensitivity of about 12 sec. arc was found to occur between 0.5 and 0.8 cyc/deg. The slightly lower threshold values found in this study probably reflect the use of a less conservative psychophysical procedure. In other respects, the results of the study are in close agreement with the present data. Taken as a whole the data indicate that the visual system is highly sensitive to small differences in disparity over space.

iii) Similarities between motion parallax and stereopsis

As mentioned above, the sensitivity functions for detecting depth from both motion parallax and stereopsis are remarkably similar. Since there is, in general, a close formal similarity in the task facing the visual system in extracting depth from the two sources, it is possible that the similarity of the empirical sensitivity functions reflects this underlying functional similarity.

In stereoscopic vision, the visual system has to compute the difference in position, or disparity, between corresponding elements in the simultaneous views to the two eyes, while, for motion parallax, the task is to compute the change in position over time in the successive views to one eye. The close relationship between the two depth sources is indicated by the fact that, in a stereoscopic scene, the views to the two eyes at any one time correspond to the initial and final monocular views as the observer moves through the distance separating the two eyes. The present task required the observer to detect whether a surface was corrugated in depth or was physically flat. For the parallax system, the task was to detect the change in relative position of different points of the surface over time, while for the stereoscopic system, the task was to detect the change in the relative position of different points in two static views. This formal similarity in task requirements, may be reflected in general principles of processing which give rise to similar system properties for both motion parallax and stereopsis.

Although the present data show that the absolute sensitivity of the motion parallax and stereoscopic systems are roughly comparable, it can be seen that thresholds for stereo are somewhat lower than those for parallax. From other observations it seems that the data for MEG, who shows the same absolute sensitivity for parallax and stereo, reflect a general, lower than average sensitivity to stereoscopic information. The more common pattern is one where stereo thresholds are roughly a factor of two less than parallax. Although this difference may be due to a true difference in the ability to detect changes in relative position over space rather than time, it is also possible that it is due to the procedure used for measuring parallax thresholds. Since the observer had to move from side to side while making parallax depth judgements the task was more complicated and this may have resulted in a slight elevation of threshold for parallax surfaces.

iv) Range of sensitivity to depth modulation

For both motion parallax and stereoscopic depth there was an optimal range of corrugation spatial frequencies over which depth modulation could easily be perceived. Sensitivity decreased by a factor of two within a two octave range from the region of maximum sensitivity (0.2 to 0.4 cyc/deg). This indicates that although the visual system can be sensitive to very small relative movements or disparities, this ability depends crucially on the spatial arrangement of the differential motions or disparities. Expressed another way, there is an optimal spatial area over which small changes in depth can be picked up and, from the present data, it would seem that the size of this optimal area must be fairly large, of the order of 2 to 5 degrees of visual angle.

It is interesting to compare the range of sensitivities found for detecting depth gratings, that is, sinusoidal modulations in depth, with that for detecting luminance gratings, that is, sinusoidal modulations in luminance. For luminance gratings peak sensitivity occurs at around 2 to 5 cyc/deg, a value ten times higher than the peak sensitivity for depth gratings. This difference suggests that the visual system is, in some sense, tuned to respond best to luminance profiles changing rapidly over space, whereas it responds best to relatively gradual changes in depth.

However, before accepting this argument for a limited spatial range for the processing of differential movement and disparity it is imnportant to consider other possible reasons for the decrease in sensitivity at high and low depth spatial frequencies. It might be argued that the fall off in sensitivity at high spatial frequencies is due to a resolution limit, that is, that the density of the dot pattern is too coarse to carry the depth information effectively. At the highest spatial frequency investigated in the present experiment, there were only eight rows of dots specifying each complete cycle of the sinusoidal corrugation but this seemed to be sufficient to carry the relative depth information. An earlier experiment, which measured depth thresholds at higher spatial frequencies, had used a dot density which was double that used here. When threshold data from this earlier experiment are plotted together with data from the present experiment (Figure 4.7), it can be seen that the manipulation of dot density had little effect on the threshold values. It is, of course, true that lowering the dot density below some limit will eventually affect thresholds, initially at higher spatial frequencies. This effect has been investigated in an experiment to be reported later in this chapter, and the dot density used in the present experiment was well above the limits found there. In addition, the data found by Nakayama and Tyler (1981a), in the study discussed earlier, suggests that detection of differential motion is possible at higher spatial frequencies than those that allow the detection of depth. Since parallax depth depends on detection of this movement it seems that the high frequency fall off is, at least for parallax, attributable to a limit on depth processing rather than on an inability to pick up relative motion.

With respect to very low spatial frequencies, it is possible that the fall off in sensitivity might be, at least partly, due to the reduced number of cycles visible on the screen for these stimuli. Tyler (1975a) has shown that, for line stimuli, thresholds do decrease if only one cycle of depth modulation is visible. However, his data show that this effect occurs mainly at high spatial frequencies and so it is unlikely to substantially affect thresholds for the low spatial

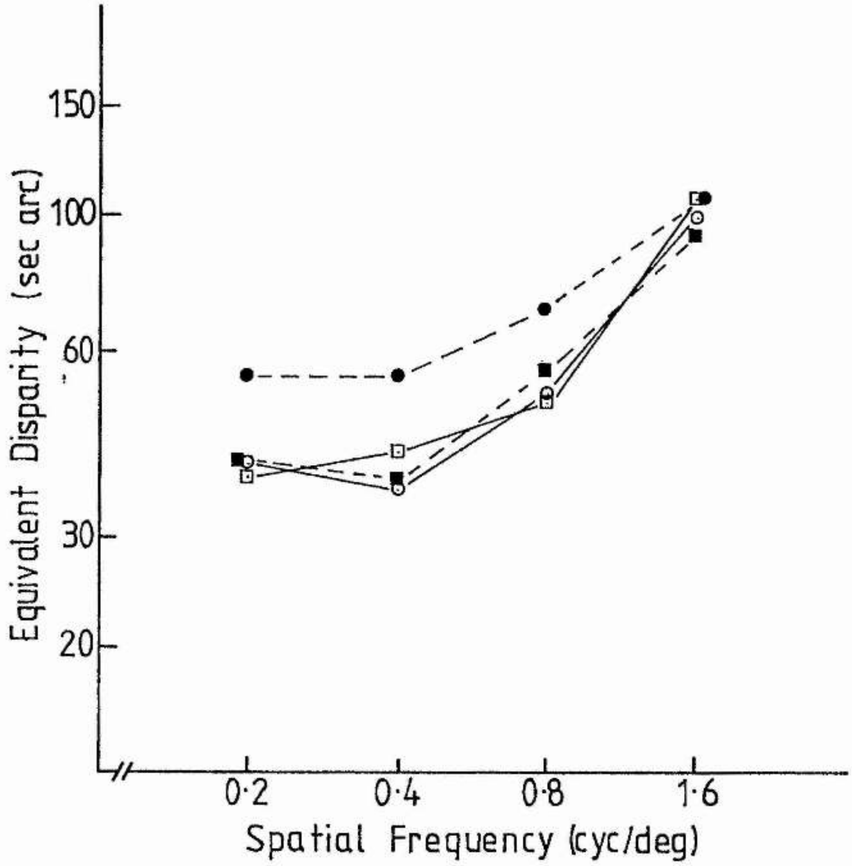


Figure 4.7.

Sensitivity functions for detecting parallax depth corrugations with random dot surface of two different dot densities. The filled lines show data from the previous figures, for observers BJR (□) and MEG (○), while the dotted lines show data measured for random dot surfaces of double the dot density for the same observers, BJR (■) and MEG (●).

frequency corrugations used here.

An interesting possibilty is that, at the low frequency end of the sensitivity function, detection is based on the depth gradients present in the pattern. That is, depth can be detected when the slope of the depth surface reaches a critical value, regardless of the area over which this slope occurs. This idea has been used to explain the perception of luminance gratings at low spatial frequencies (van der Wildt et al., 1976; Campbell et al., 1981). To determine whether this type of description is appropriate for depth gratings the threshold data can be plotted in terms of the surface slope at threshold. The data have been plotted in this way in Figure 4.8, where the slope of the sinusoidal depth grating has been approximated as the slope of a triangular corrugation of the same amplitude. Although clearly, at frequencies of 0.2 cyc/deg and above, detection is not being made on the basis of the slope reaching a crucial value, the data for the two lowest spatial frequencies show that the slope at threshold is similar for all three subjects. The data is not sufficient to allow firm conclusions but is at least suggestive. Further data relevant to the detection of depth gradients will be considered later in the chapter.

In summary, it seems probable that the limited range of sensitivity for depth modulation reflects a real limit in the processing of depth change for both motion parallax and stereopsis. A hypothesis arising from this finding is that the range of spatial extents found for mechanisms underlying depth processing, will be limited. From the present data the probable spatial extent would be fairly large, extending over several degrees of visual angle. From an ecological point of view, it seems to make sense that the sensitivity

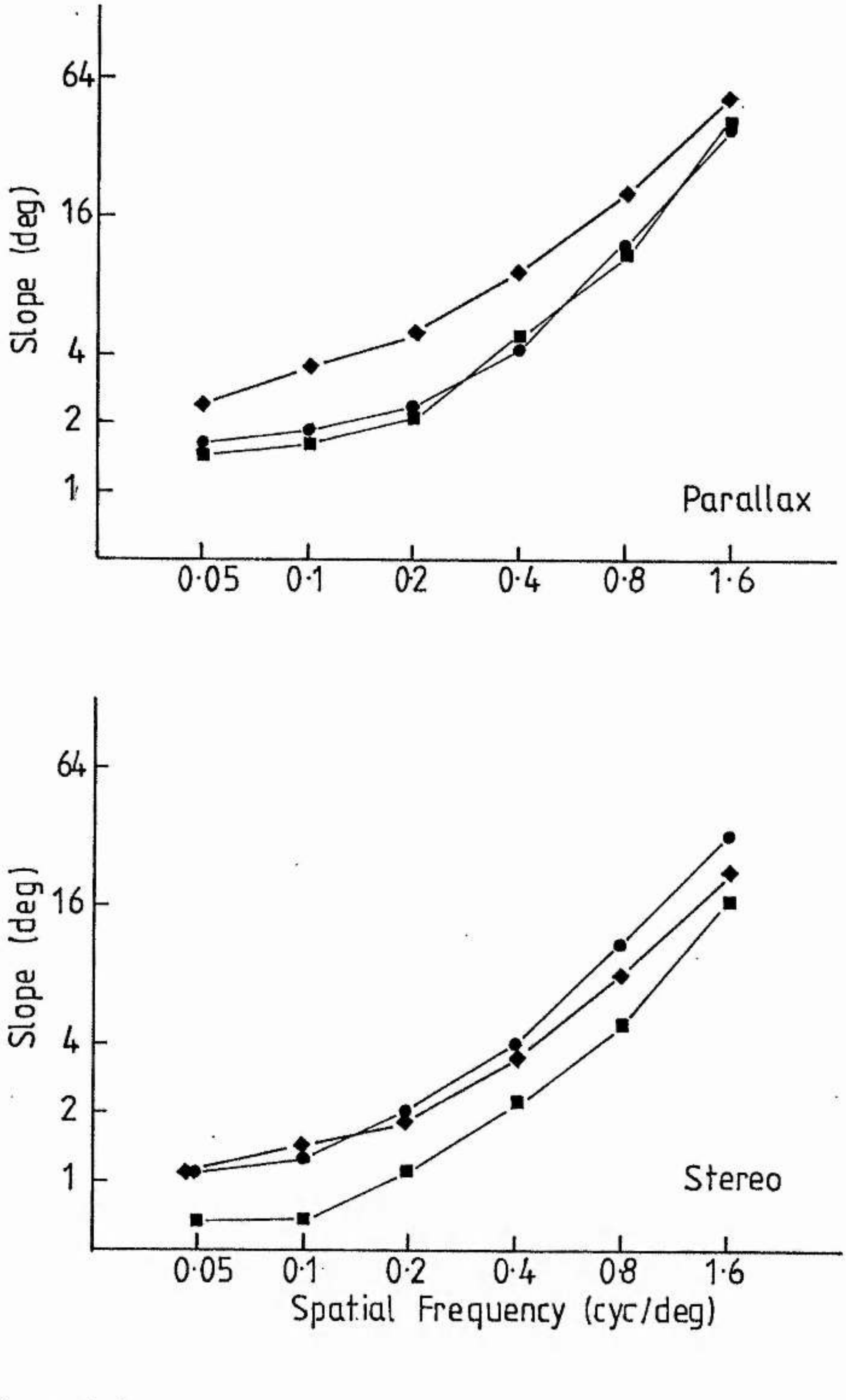


Figure 4.8.

The data from Figures 4.4 and 4.5 replotted to show the threshold depth slope for detecting depth corrugations of different spatial frequencies. Data are shown for three observers, BJR (■), MEG (●) and JGQ (◆), when the depth surfaces were specified by motion parallax (upper) and by stereoscopic information (lower).

function for depth change should be shifted towards lower frequencies than that for luminance change. The natural environment contains objects and surfaces which change fairly gradually in depth and does not contain repetitive patterns of high frequency depth change like those commonly found for luminance (high density textures, for example). An ability to pick up low frequency depth change would seem to be an advantage for object recognition and locomotion while an insensitivity to high frequency change would not seem to have any obvious detrimental effect on the ability of an organism to act effectively in its environment.

4.5 Further studies of motion parallax sensitivity.

The second half of this chapter describes some further studies which have measured thresholds for perceiving corrugated depth surfaces under various conditions. Most of these experiments represent preliminary studies which need to be replicated in more detail before firm conclusions can be drawn. They are included here, however, to indicate that the basic characteristics of the depth sensitivity functions are consistently observed in different experimental designs and procedures. The data, although not conclusive, also highlight some interesting areas for further theoretical discussion and empirical investigation.

i) Depth thresholds using forced-choice procedures

In the experiments described so far, the depth thresholds were measured using an ascending method of limits. As the depth amplitude of the corrugated surface was gradually increased, the point at which observers could correctly identify the shape of the depth surface, was taken as the threshold. Observers had to identify both the number of cycles and the phase of the corrugated surface, and this therefore represents a fairly conservative procedure for determining depth thresholds. As suggested above, the use of a forced-choice psychophysical procedure to measure thresholds for stereoscopic corrugations was one possible reason for the slightly lower thresholds found in the study by Schumer and Ganz (1979). In general, forced-choice procedures are preferable in psychophysical research as they provide a measure of threshold which is not affected by changes in observer criteria, but they are rather too time consuming for widespread use in outlining basic system parameters over a wide variety of conditions. It was decided, however, to confirm the pattern of thresholds obtained with the previous method, by measuring the sensitivity functions for both motion parallax and stereoscopic depth using a forced-choice frequency method.

The motion parallax and stereoscopic displays described earlier were used to present sinusoidally corrugated depth surfaces specified by relative motion or binocular disparities, respectively. An identical forced choice frequency method was used to determine depth thresholds for both parallax and stereo surfaces. Initial threshold values, for corrugated surfaces at each of six depth spatial frequencies, were determined using the ascending method of limits already described. For each frequency six values of peak to trough depth amplitude were then chosen to span the initial threshold value. Thresholds were measured in separate sessions for each spatial frequency and each session consisted of a series of two-interval trials. On each trial a depth grating at one of the six amplitude values was presented randomly in one of the two equal intervals and during the other interval a flat random dot surface was presented. The observer's task was to identify the interval in which the grating appeared. To avoid the possibilty of detecting the correct interval on the basis of the change in depth at the interval boundary, the onset and offset of the grating were gradual. The amplitude of the depth grating increased slowly from zero to the appropriate amplitude for that trial, over a period of two seconds, and also decreased gradually to zero over the final two seconds of the interval. Both intervals were six seconds long and a bell sounded at the beginning and the end of each interval. At the end of the trial the observer pressed a key to signal which of the two intervals had contained the depth grating and the next trial followed in a couple of seconds. Each session consisted of a random sequence of trials comprising twenty presentations of the depth grating at each of the six amplitude values.

For each spatial frequency, the percentage correct at each amplitude was calculated and the 75% correct value was read from the resulting psychophysical function. This value was taken as the threshold for that frequency. The data are plotted in Figure 4.9 for corrugated depth surfaces specified by both parallax and stereoscopic information. It can be seen that, as for the thresholds described previously, the peak sensitivity occurred at around 0.2 to 0.4 cyc/deg and sensitivity decreased for frequencies above and below these values. Although the shape of the function was basically the same it appeared to be somewhat flatter in this experiment. In absolute terms, thresholds for parallax and stereoscopic depth were roughly the same for this observer, again reflecting the data found in the previous experiment. The peak sensitivity was about 25 sec arc disparity , or

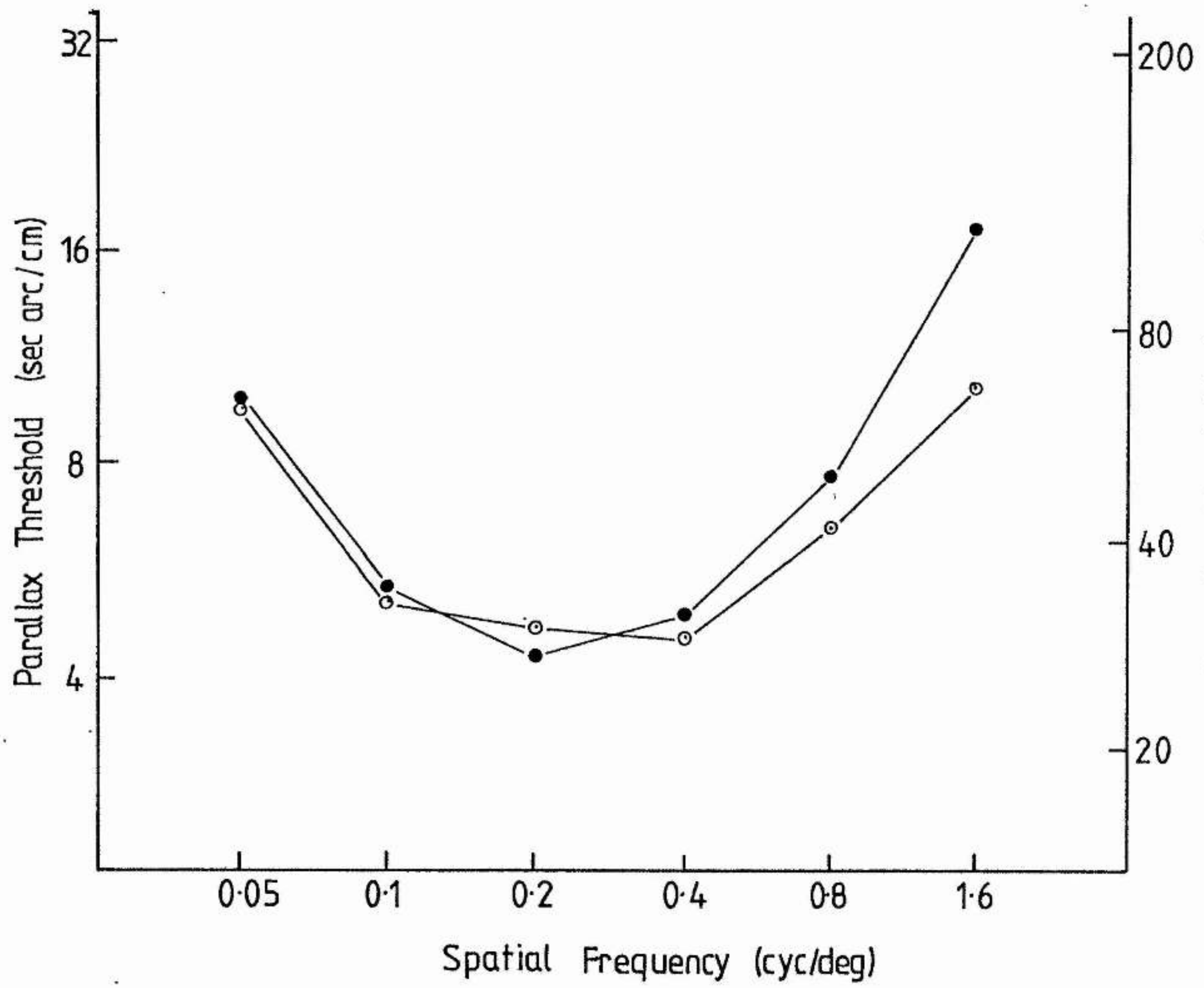


Figure 4.9.

Thresholds for detecting corrugated depth surfaces specified by motion parallax (o) and stereoscopic (•) information. Data were measured using a forced-choice psychophysical procedure for observer MEG. Data points show the 75% correct level for each spatial frequency.

equivalent disparity, and this is about 20% lower than that found with the previous procedure.

In conclusion, the threshold data measured here, using a forced choice psychophysical procedure, gave essentially the same sensitivity function as that obtained using an ascending method of limits. The absolute sensitivity was, however slightly lower overall and this reflects the less conservative nature of the forced choice task which merely requires detection of the presence of the depth grating and not identification of its shape.

ii) Thresholds for random dot surfaces containing fewer dots.

The threshold measurements described so far have used a high density random dot pattern to carry the depth information from relative motion or disparity. The pattern consisted of an array of 256 by 256 dots and each dot was set to be either bright or dark with a 50% probability. Hence, the pattern consisted of over 32,000 dots scattered randomly over the screen. By decreasing the probability with which the dots in the array are made bright, random dot patterns containing fewer bright dots could easily be produced.

For both parallax and stereo depth surfaces observers reported that the phenomenal impression of a solid, corrugated depth surface remained even when the number of dots specifying the surface was only a few hundred. However, there is clearly a lower limit on the number of dots needed to specify a corrugated depth surface. In particular, the ability to perceive high spatial frequency corrugations should break down before the ability to perceive corrugations of lower frequencies, since more dots are required to specify rapid changes in depth. As a preliminary investigation of the effect of reducing the number of dots, thresholds were measured for detecting depth in corrugated surfaces specified by parallax information. Thresholds for one observer, were measured for three spatial frequencies using seven random dot patterns which contained different numbers of dots.

Parallax information specifying sinusoidally corrugated depth surfaces of 0.1, 0.2 or 0.4 cyc/deg was provided in the usual way. Patterns of relative motion, linked to movement of the observer, were introduced into a random dot pattern presented on an oscilloscope screen. The pattern which carried the relative motion contained a number of bright dots which ranged from over 32,000 to under 200. For each pattern the dots were scattered randomly over the entire oscilloscope screen, which subtended 20 by 25 degrees of visual angle. In each session, one of the seven dot patterns was chosen at random and thresholds for detecting the corrugated surfaces were measured using the ascending method of limits described previously. Ten thresholds were measured at each spatial frequency in a random order.

The observed thresholds for detecting parallax depth are shown in Figure 4.10 for the three spatial frequencies. The data are plotted as a function of the number of dots in the pattern carrying the relative motion information. As the number of dots decreased, thresholds rose fairly steadily for the 0.4 cyc/deg corrugation. Thresholds for the 0.2 cyc/deg corrugation started to rise when the number of dots fell below about 2000, and for the 0.1 cyc/deg corrugation, they started to rise only when the number of dots went below 500.

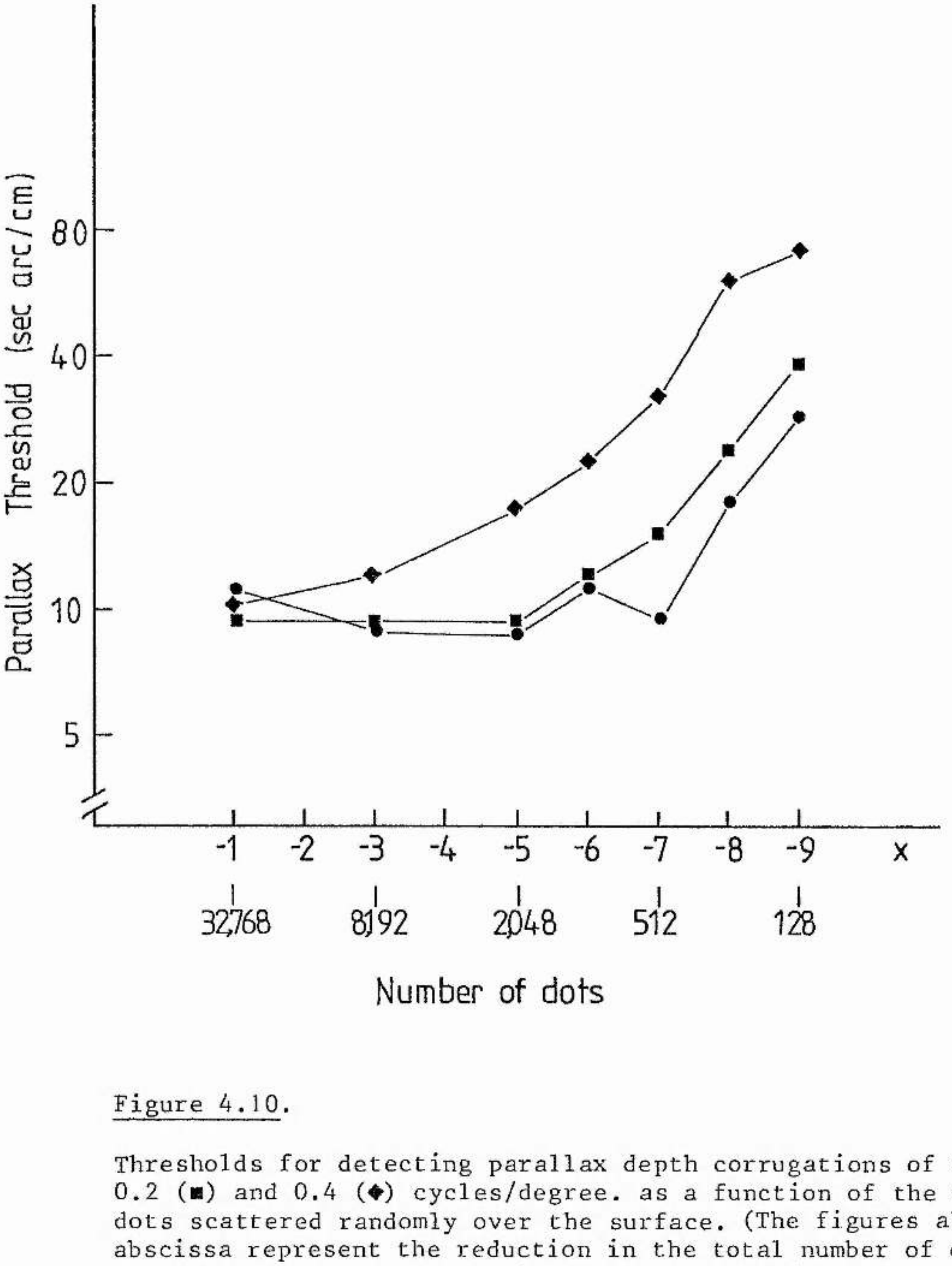


Figure 4.10.

Thresholds for detecting parallax depth corrugations of 0.1 (●), 0.2 (■) and 0.4 (◆) cycles/degree. as a function of the number of dots scattered randomly over the surface. (The figures along the abscissa represent the reduction in the total number of dots and the actual number of bright dots present (shown below) can be calculated from the formula no.=$256^2/2^x$).

The data therefore followed the expected pattern, with, sensitivity to high spatial frequency depth gratings falling off more rapidly as the number of dots in the pattern decreased. Observers reported that as the number of dots became very low for the 0.4 cyc/deg surface, the phenomenal impression at threshold changed from the perception of a smooth depth surface to the perception of separate isolated dots which appeared to lie at different depths. In summary, although in the limit thresholds for detecting depth gratings do seem to depend on the number of dots available to specify the depth information, the levels of dot density used in previous threshold experiments have been above this limit.

iii) Thresholds as a function of viewing distance

It was noticed informally that when motion parallax depth surfaces were viewed at increasing distances the amount of perceived depth within the surface increased, even when the amount of relative movement on the retina was arranged to be the same at each distance. This finding indicated that some kind of depth constancy mechanism was in operation where the perceived depth depended on the perceived distance of the surface as well as the retinal relative motion. This seems to be similar to the stereoscopic depth constancy effects described and reviewed by Ono and Comerford (1977). Depth constancy is of course an important feature built into depth processing since, in the everyday environment, the same amount of relative movement, or disparity, is produced by surfaces with different depths at different distances. The presence of a depth constancy mechanism for motion parallax raises the possibility that thresholds for perceiving parallax depth might not depend on the retinal relative movement reaching a critical value but rather, that they might depend upon the depth in the surface reaching a critical value. For example, a certain small amount of retinal relative movement will specify a small depth difference at near distances or a large depth difference at far distances and, if threshold depends on depth, this amount of relative motion might be below threshold at nearer distances but above it at farther distances. In order to separate these two possibilities it is necessary to look at thresholds for detecting parallax depth when the depth surfaces are presented at different distances.

Thresholds were, therefore, measured for detecting depth in corrugated parallax surfaces which were presented at three different observation distances. Parallax depth surfaces were produced in the usual way. The observer moved from side to side on the chinrest and viewed the transforming pattern on the scope which was positioned at either 57, 114 or 228 cms from the observer. At each distance, thresholds were measured using an ascending method of limits, for corrugated surfaces with spatial frequencies of 0.2, 0.4 and 0.8 cyc/deg. To keep spatial frequency constant the number of cycles present on the screen for each frequency was altered according to the observation distance. To avoid the confounding effects of dot density, the density of the random dot pattern was also adjusted so that, at each distance, each element of the pattern subtended the same visual angle. When this was done the random dot pattern consisted of a 256, 128 or 64 dot square array at 57, 114 and 228 cms, respectively, with the probability of a bright dot being 50% in each case.

A few data points were collected in a condition where the overall size of the pattern on the screen was altered at each distance to ensure that it always subtended 6 by 5 deg of visual angle. In this case, at each distance, the pattern consisted of an array of 64 by 64 dots and there was always 1,2 or 4 cycles of the corrugation visible for spatial frequencies of 0.2, 0.4 and 0.8 cyc/deg respectively.

The data for two observers are shown in Figure 4.11a, where threshold is plotted as a function of spatial frequency for each of the three distances. The filled lines show data for a full screen display at each distance whereas the dotted lines show data points for a display of constant angular size. For each data line the sensitivity function shows its usual shape with thresholds beginning to rise by 0.8 cyc/deg, although at the farthest distance the function is more level. The threshold values are expressed as the amount of peak to trough relative movement at threshold in millimetres per degree of head movement. This means that, if threshold depends on the amount of retinal relative movement, then the threshold value in millimetres should increase by a factor of two when the observation distance is doubled. As can be seen the data closely approximate this pattern with threshold values roughly doubling between observation distances of 57 and 114, and 114 and 228 cms. To emphasise this point the data have been replotted in Figure 4.11b where threshold has been expressed in min. arc per degree of head movement. In angular terms, thresholds are roughly similar for all viewing distances. There is, however, a deviation from this pattern for the highest spatial frequency at the farthest distance. Here threshold is less than would be expected and the reason for this discrepancy is not clear.

Although it did not appear to affect thresholds, depth constancy was operating in this experiment since at farther distances observers

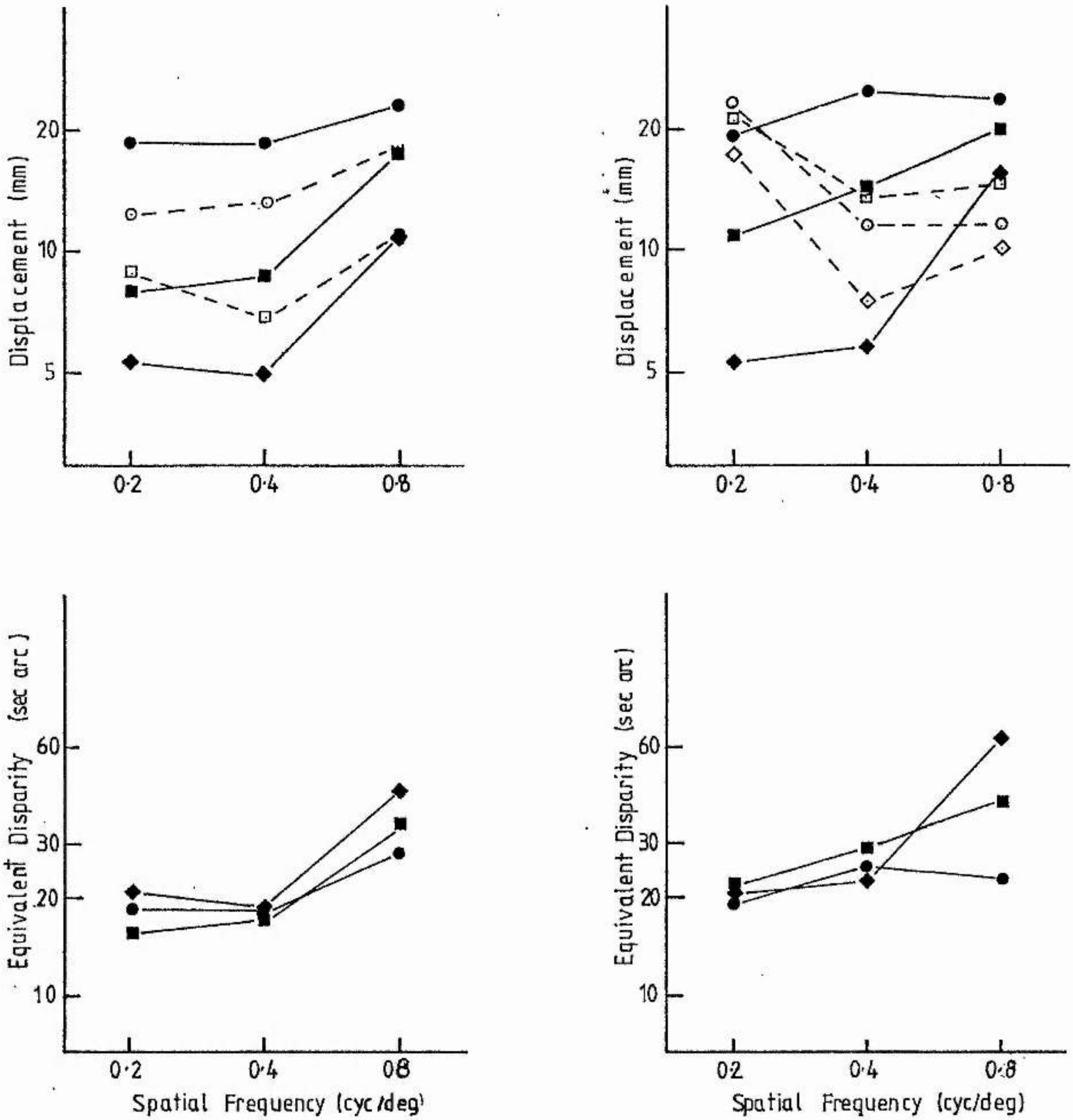


Figure 4.11.

Parallax depth thresholds for surfaces presented at different distances from the observer. In (a) thresholds for detecting surface at 57 (◆), 114 (■) and 228 (●) cms. from the observer are expressed as the amount of peak to trough relative motion in mm. that was needed to detect the depth surface.The dotted lines show additional data collected when the angular size of the surface was made equal at each observation distance. In (b) the data have been plotted so that the thresholds are expressed in angular terms as sec arc equivalent disparity. Data are shown for two observers, MEG (left) and RF (right).

found that the amount of perceived depth at threshold was very large indeed. As the peak to trough depth amplitude was slowly increased to threshold a surface containing a large amount of depth suddenly appeared. In contrast, at nearer distances, a slight depth modulation would only gradually become apparent. In summary, despite the operation of depth constancy, thresholds for perceiving depth in parallax surfaces depend on the retinal relative movement between the images of different parts of the surface and not on the simulated or perceived depth within the surface.

iv) Sensitivity for depth surfaces with profiles of different shapes

In the luminance domain, sensitivity to luminance distributions with differently shaped profiles has been used to investigate the basis of luminance processing in the visual system. It is widely accepted that the visual system uses some form of spatial frequency analysis which involves separate processing of the different spatial frequency components of the overall luminance pattern (Sachs, Nachmias and Robson, 1971; Graham, 1975; Wilson and Bergen, 1979). Campbell and Robson (1968) have compared the contrast sensitivity functions for detecting luminance gratings with square and sinusoidal profiles and this has provided one line of evidence for such an analysis. They found that the sensitivity function for a square grating does not show the fall off in sensitivity at low spatial frequencies that is commonly found for sine gratings. In addition, the overall sensitivity for square gratings is heightened by an amount which corresponds to the increased amplitude of the fundamental component of the square wave compared with that of a sine grating of the same amplitude. On the other hand, evidence against this model has been found by Campbell, Johnstone and Ross (1981) who also measured sensitivity to luminance gratings with differently shaped profiles. By measuring sensitivity for trapezoidal luminance gratings of different ramp widths from square to triangle, they have argued that, at the low frequency end of the sensitivity function, detection is based on contrast gradients and not on the detection of spatial frequency components.

In the hope of using analogous techniques to investigate depth processing, thresholds were measured for surfaces corrugated in depth with differently shaped depth profiles. Depth information was specified by motion parallax in the usual way, and to specify corrugated surfaces of different shapes, the shape of the distortion signal used to provide the relative motion was altered appropriately. Other display characteristics and procedures were the same as those used in previous experiments.

The phenomenal appearance of the four differently shaped corrugated surfaces with sine, square, ramp and triangle shaped profiles was illustrated in Figure 3.4a. Sensitivity functions were measured for one observer, for detecting depth in corrugated surfaces of these four shapes, and these functions are plotted in Figure 4.12b. As before, the region of peak sensitivity was found to be between 0.2 to 0.4 cyc/deg and this was true for corrugations of all shapes. Overall, sensitivity was greatest for corrugations with square-shaped profiles, then sine, then triangle, then ramp profiles. If detection of depth gratings was based on some kind of depth spatial frequency analysis analogous to that in the luminance domain then threshold should depend on the fundamental component of the depth grating. The

	Square	Sine	Triangle	Ramp
Maximum Slope	?	1	0·64	0·32
Predicted Order	?	1	2	3
Amplitude of Fundamental	1·27	1	0·81	0·64
Predicted Order	1	2	3	4

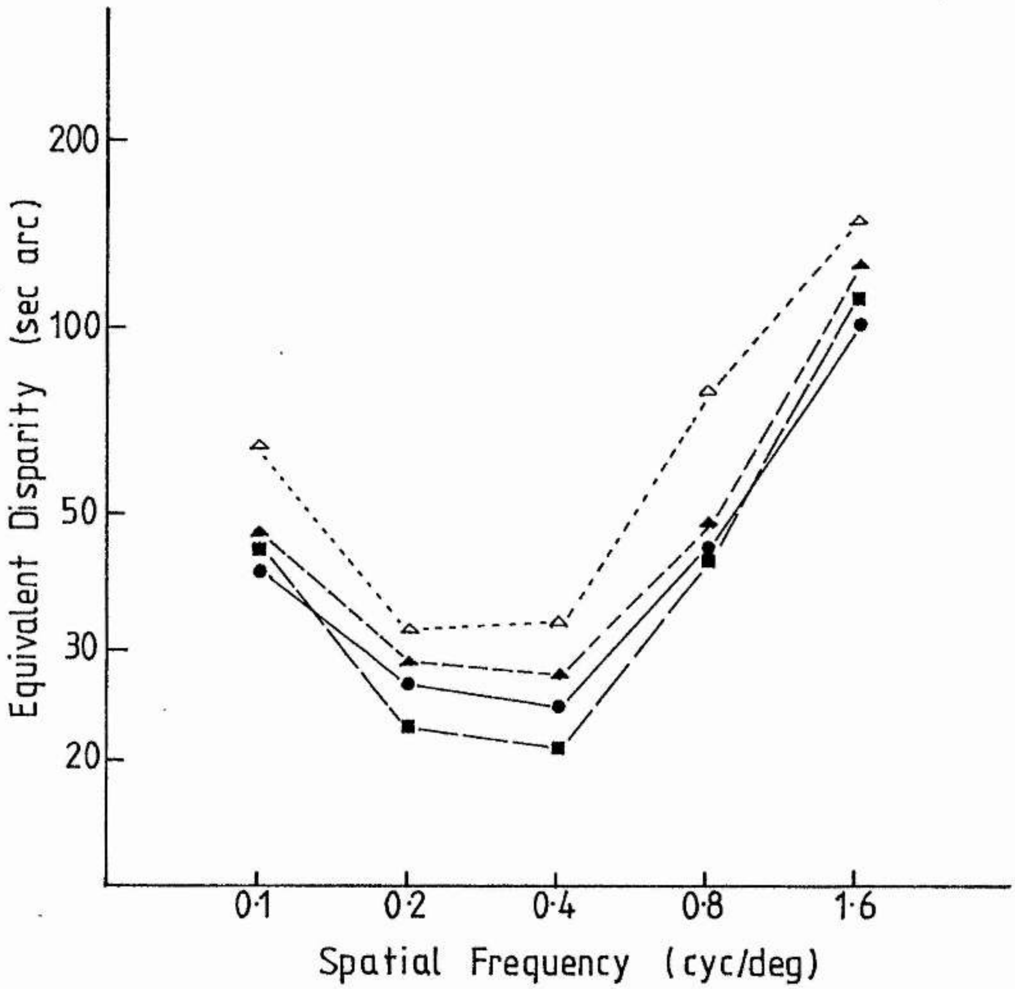
(a)

Figure 4.12.

Parallax depth thresholds for corrugated surfaces with different shaped depth profiles.

(a) The predicted order of sensitivity for corrugated surfaces of four shapes based on either the maximum slope within the depth surface or the amplitude of the fundamental depth spatial frequency of the surface.

(b) Thresholds for detecting square (■), sine (●), triangle (▲) and ramp (△) shaped depth corrugations as a function of the spatial frequency of the corrugation. (Observer BJR).



200
100
50
30
20
Equivalent Disparity (sec arc)
0·1
0·2
0·4
0·8
1·6
Spatial Frequency (cyc/deg)

(b)

amplitude of the fundamental varies for the differently shaped profiles and the relative amplitudes are shown in Figure 4.12a. The predicted order of relative sensitivity from this analysis is in fact the same as the observed order shown in Figure 4.12b. However, it is also possible that an explanation where detection depends on the first and second spatial derivatives of depth change in the different profiles could also be advanced which would make the same prediction. If, for example, thresholds depend on the slope of the depth surface reaching a critical value then the predicted order for sine, triangle and ramp surfaces is the same as the spatial frequency prediction (Figure 4.12a). It is not clear what prediction would be made for the square depth profile since it is unclear how to evaluate this profile in terms of slopes or depth gradients. The differences between the spatial frequency and depth gradient predictions is a quantitative rather than a qualitative one. With the present design and procedures the differences between the sensitivity to the differently shaped surfaces was too small to adequately test the quantitative predictions from these two models.

Other evidence relating to whether depth processing involves an analysis of a depth surface into different spatial frequencies of depth change will be considered in the next chapter. The present data throw some doubt on this possibility since there is a marked decrease in sensitivity at the lowest spatial frequency even for a depth corrugation with a square shaped profile. This decrease would not be predicted from a simple frequency model.

In Figure 4.13, the parallax depth thresholds are plotted for another subject for square, trapezoidal and triangle shaped depth

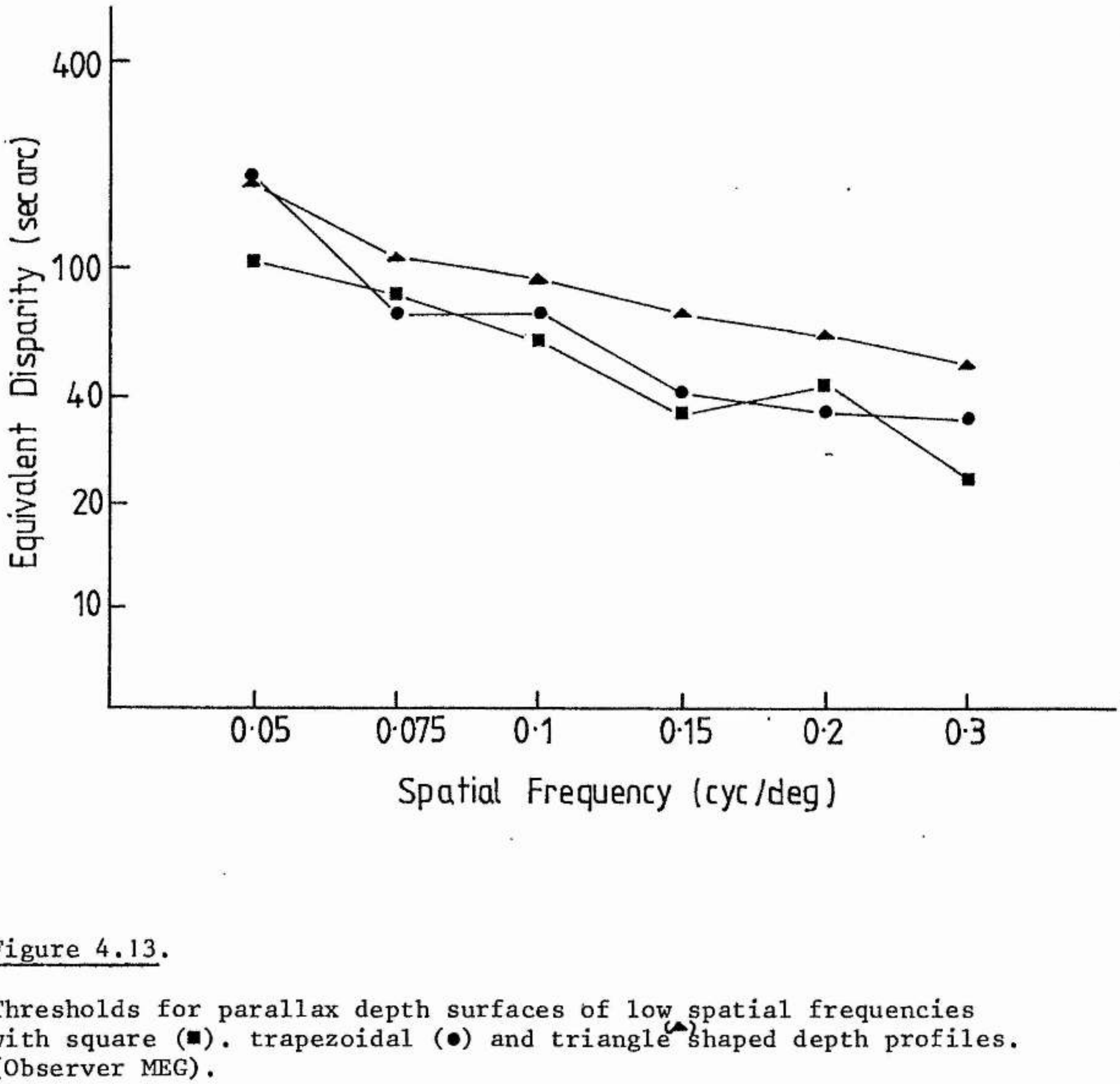


Figure 4.13.

Thresholds for parallax depth surfaces of low spatial frequencies with square (■). trapezoidal (●) and triangle (▲) shaped depth profiles. (Observer MEG).

corrugations of low spatial frequencies. The trapezoidal surface had a ramp width equal to half that of the triangular surface of the same amplitude and spatial frequency, and was flat during the rest of the cycle. It was, therefore halfway between a triangular and a square shaped corrugation. The data clearly suggest that thresholds for the trapezoidal corrugation are similar to those for the square corrugation, and both are less than those for the triangular corrugation. The difference in sensitivity was, however, not sufficient to allow a detailed investigation of sensitivity to a whole range of trapezoidal waveforms with different ramp widths. Such an analysis would have indicated whether detection of these surfaces was based on depth gradients. It is interesting that, at threshold, the appearance of corrugations of all three shapes was reported to be very similar and all appeared rounded in depth. The investigation of thresholds for differently shaped surfaces would seem to be a fruitful area for future investigation if more appropriate techniques were applied.

v) Depth thresholds for a stereoblind observer

As has been widely documented and investigated the ability to use stereoscopic information varies widely between individuals (Richards, 1970, 1971a; Julesz, 1971). Stereo vision is, of course, not available for people who have lost the sight of one eye, and is also absent for some who have suffered severe squint or astigmatism. The loss of stereoscopic vision does not, however, seem to drastically affect the ability of these individuals to act effectively in the environment and the high standards achieved in sport and athletics by individuals with monocular vision, attests to this fact. Motion parallax surfaces produced using the techniques described in this thesis have now been shown to several hundred individuals and every observer has been able to perceive depth in the surface. Motion parallax seems, therefore, to be a source of information less susceptible to individual variation perhaps because it only requires adequate vision in one eye. It seems likely that stereo-deficient observers would rely heavily on motion parallax as a source of depth information and the question arises as to whether these individuals are able to use parallax information more effectively than people with adequate binocular vision. A reliance on motion parallax might result in a greater sensitivity to relative motion transformations and so it might be expected that thresholds for perceiving parallax depth would be lower for stereoblind observers.

To investigate this possibility, a sensitivity function for parallax depth surfaces was measured for a stereoblind observer who had vision in only one eye. Thresholds were measured using the normal display and procedures and the data are plotted in Figure 4.14. Apart from a marked insensitivity to the lowest frequency tested the sensitivity function was very similar to those obtained for observers with adequate stereo vision. Peak sensitivity, which occurred as usual at 0.2 to 0.4 cyc/deg, was around 13 sec arc per deg of head movement. This sensitivity is within the range normally observed but does not represent a very high sensitivity to parallax depth. For example, two of the observers in the experiment described at the beginning of this chapter, showed thresholds which were a factor of two lower than this.

Hence, at least for this stereoblind observer, sensitivity for parallax depth was not heightened by a greater reliance on motion

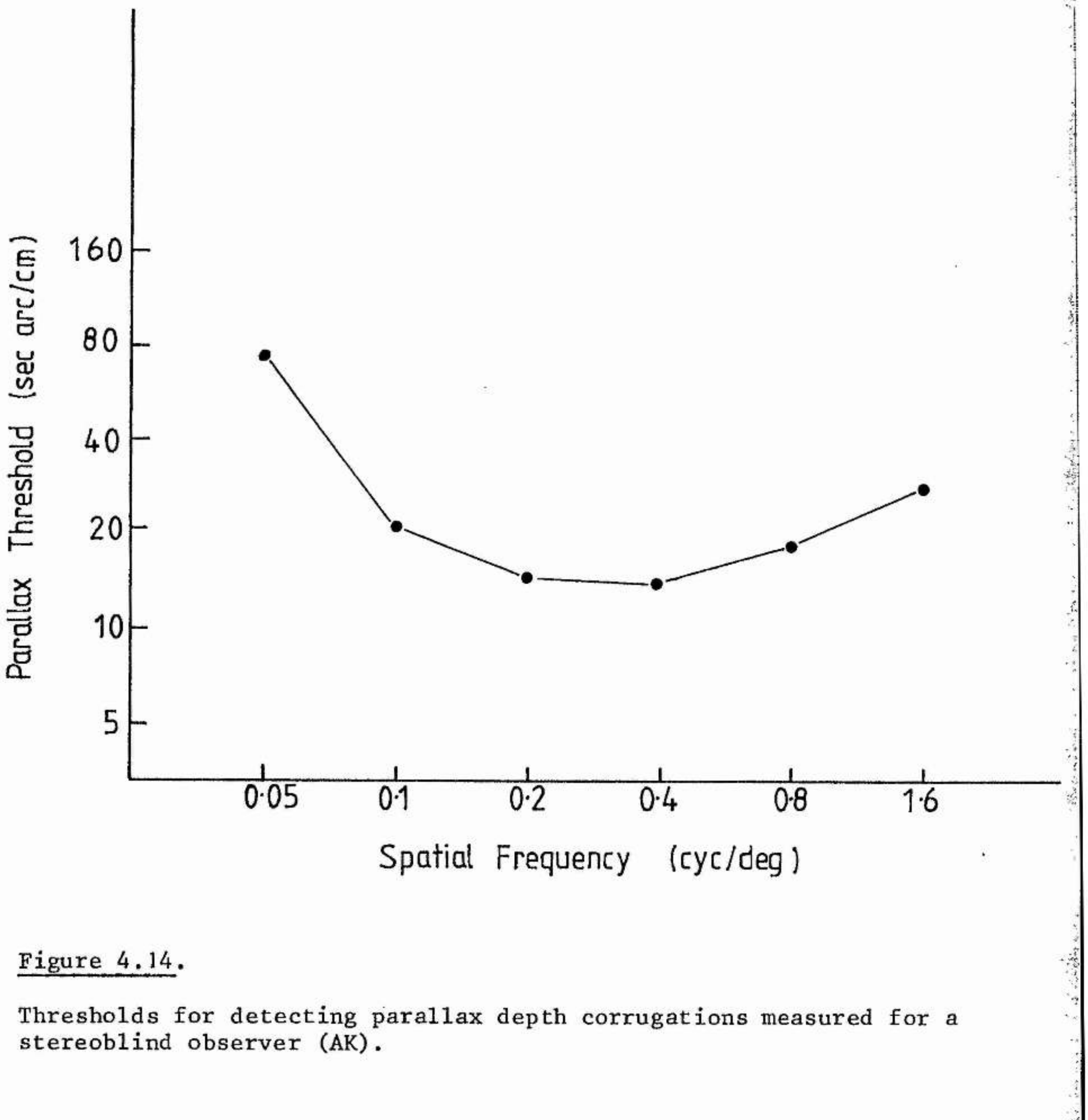


Figure 4.14.

Thresholds for detecting parallax depth corrugations measured for a stereoblind observer (AK).

parallax as a source of depth information.

The experiments described in this chapter have looked at the sensitivity of the visual system to depth modulations specified by relative motion or disparities. The sensitivity functions have shown that there are close similarities between the threshold characteristics of the parallax and stereoscopic processing systems. They have also suggested that there might be an optimal area over which differential motion or disparity can be picked up. The experiments reported in the following chapters describe some suprathreshold depth effects which have provided further indications of the nature and spatial extent of the mechanisms underlying depth processing. These effects have also confirmed the close similarity between motion parallax and stereopsis.

Chapter 5 Successive Contrast Effects in the Depth Domain

Contrast effects have been extensively reported and investigated throughout the history of visual perception. Successive contrast effects or aftereffects describe perceptual effects where the phenomenal impression of a stimulus is affected by the stimuli which have been presented previously. Simultaneous contrast effects, on the other hand, occur when the perceived nature of a stimulus is affected by stimuli adjacent in space, rather than time. The two types of contrast effect are, therefore, a result of either temporal or spatial interactions. It has been known since Aristotle, for example, that prolonged viewing of a bright disk gives rise to a complementary afterimage and that a grey disc with a light surround appears darker than a comparable disc with a dark surround. Similarly, coloured afterimages and colour contrast (where a grey disc takes on the complementary colour to its surround) were noted and studied by Leonardo da Vinci (see Boring, 1942). Over the last hundred years it has become apparent that similar successive and simultaneous contrast effects occur in many visual dimensions and these have been widely studied (Helmholtz, 1925; Hering 1886; Wohlgemuth, 1911; Gibson, 1933). Recently, one of the major reasons for studying successive and simultaneous contrast effects has been the belief that such effects can be used to elucidate the properties of the mechanisms underlying visual processing (Sutherland, 1961; Blakemore and Sutton, 1969; Mollon, 1974; Anstis, 1975; Frisby 1979). It has been argued that successive contrast effects provide evidence for the existence of specific processing mechanisms, for example, mechanisms responsive to different spatial frequencies (Blakemore and Sutton, 1969). Simultaneous contrast effects, on the other hand, indicate the spatial extent over which such processes operate (Ratliff, 1965; von Bekesy, 1968).

Within this general framework, both successive and simultaneous contrast effects have been studied in the depth domain. The experiments described in this chapter were designed to investigate successive contrast effects for depth surfaces specified by motion parallax information. For comparison, aftereffects for stereoscopic depth were also investigated. Studies of simultaneous depth contrast are described in the following chapter.

5.1 Successive contrast effects.

Successive contrast effects following prolonged stimulation, can be demonstrated in many sensory dimensions. The best known example is probably the waterfall illusion or movement aftereffect (Wohlgemuth, 1911) where after prolonged viewing of a surface moving in one direction, a stationary pattern appears to move in the opposite direction. This type of contrast effect is an example of a negative aftereffect where a neutral test stimulus takes on properties complementary to those of the adapting stimulus (Favreau and Corballis, 1976). Another type of contrast effect occurs when prolonged viewing causes shifts in the perceived characteristics of subsequently viewed stimuli. For example, after prolonged viewing of a luminance grating at one spatial frequency, the frequency of a test grating at a neighbouring spatial frequency is misperceived (Blakemore and Sutton, 1969). In both cases the aftereffect is thought to arise from the adaptation of mechanisms within the visual system which become fatigued through prolonged stimulation (Sutherland, 1961; Blakemore and Sutton, 1969; Coltheart, 1971). Alternatively, some authors suggest that aftereffects arise from prolonged inhibition between mechanisms following adaptation (Dealy and Tolhurst, 1974). It is not clear whether negative aftereffects and those which produce shifts in perceived stimulus values can be explained by the same underlying organisation of processing mechanisms. Recently, however, both types of motion aftereffect have been attributed to changes in the overall response distribution of independent tuned channels (Mather and Moulden, 1980).

Within the field of depth perception, there have been several reports of illusory depth effects which follow prolonged viewing of three-dimensional stimuli. For example, Kohler and Emery (1947) reported that inspection of a stimulus which sloped away from the observer in depth, affected the perception of a subsequently viewed stimulus in the frontoparallel plane, so that it appeared to slope toward the observer. Other authors have shown that the distance to a figure or surface will often be misperceived after prolonged viewing of a stimulus at a different distance (Ames, 1935; Howard and Templeton, 1964). However, since these studies used real three-dimensional objects and displays, there were generally several sources of depth information available to the observer and this made it impossible to attribute the aftereffects to any one source. Moreover, from these studies it is not possible to conclude that the reported aftereffects were generated by adaptive mechanisms within depth processing systems. Instead, it is possible that the aftereffects were a result of adaptation within local size or orientation processing units, since two-dimensional information about form was also available to the observer.

This problem can be overcome if random dot stereograms (Julesz, 1960; 1971), are used as adapting stimuli. This ensures that the depth cue of stereopsis is isolated from other confounding variables. The depth surface perceived in a random dot stereogram is not present in either monocular view alone and, since the depth relationships are specified only by binocular disparities, any depth aftereffect which follows inspection of such a surface can, therefore, only have resulted from the adaptation of mechanisms at the level of stereopsis or beyond. Random dot stereograms were used by Blakemore and Julesz (1971) to demonstrate, unequivocally, that depth aftereffects follow prolonged inspection of stereoscopic depth surfaces. Their experiment is illustrated in Figure 5.1. Observers were shown a random dot stereogram which portrayed a depth surface containing two squares, one above the other, which stood out in front of a background. The upper square was at a greater crossed disparity than the lower square and so it appeared to lie closer to the observer. After viewing the surface for a minute, observers were shown a test stereogram containing two squares at the same disparity, which would normally have appeared to lie at the same depth. Observers reported that the squares in the test stereogram appeared to lie at different depths, and the upper square appeared to lie farther away than the lower square, that is, the perceived depth difference was in the opposite direction to that in the adapting surface. Blakemore and Julesz went on to measure the size of the aftereffect by introducing a physical disparity between the two squares in the test stereogram until the aftereffect was cancelled out and the two squares appeared to lie in the same depth plane. They found that, if the difference in disparity between the two squares in the adapting stereogram was 4 minutes of arc then the subsequent aftereffect was cancelled by introducing a differential disparity of 1

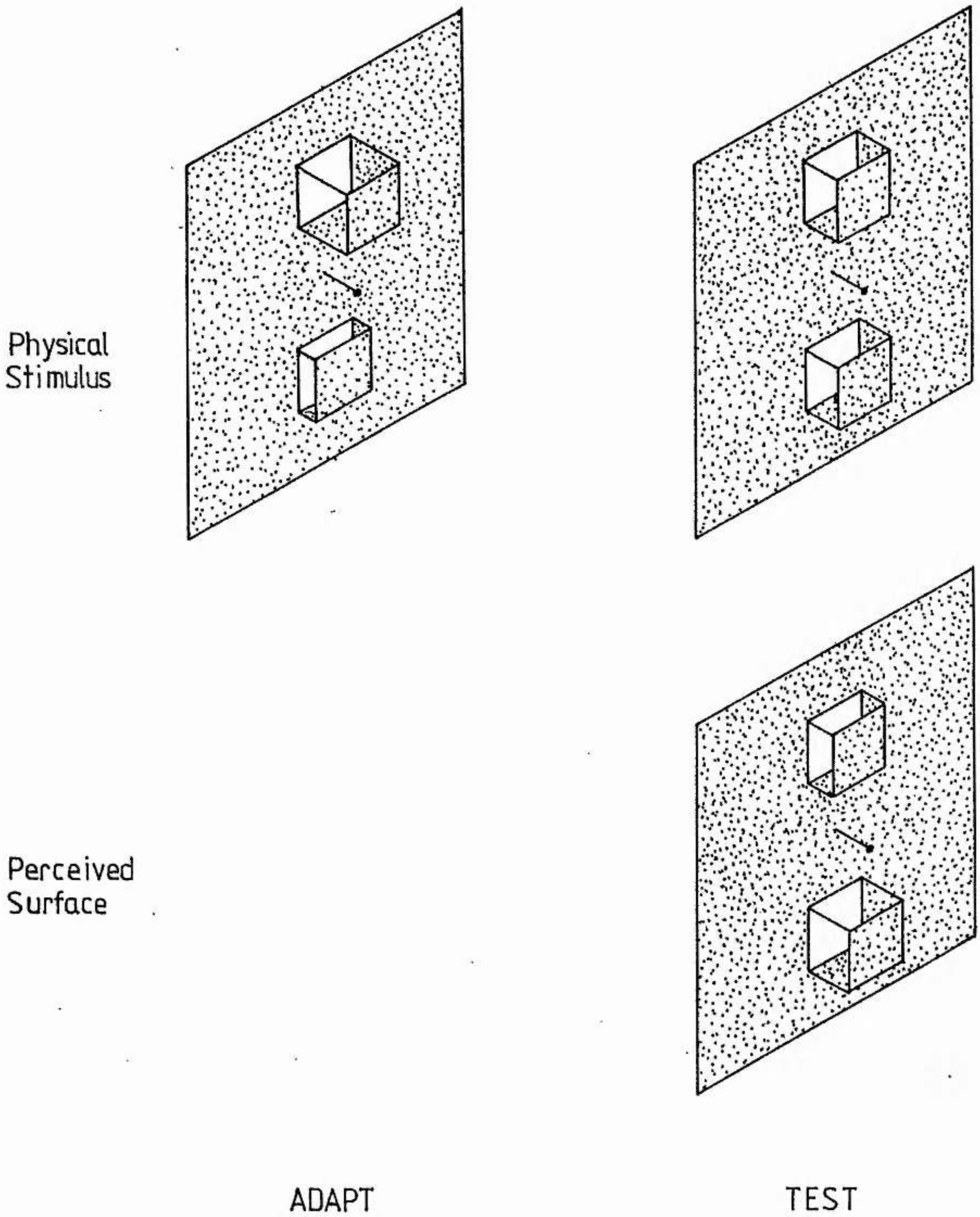


Figure 5.1.

The depth surfaces used to demonstrate stereoscopic depth aftereffects by Blakemore and Julesz (1971). After prolonged viewing of an adapting surface containing an upper square in front of the fixation point and a lower square behind, a test surface was presented which contained two squares in the plane of the fixation point. The two squares in the test surface appeared to lie at different depths, the lower appeared to be nearer the observer than the upper.

minute of arc between the two squares in the test stereogram. Expressed as a percentage, the strength of the aftereffect was therefore about 25%.

More recently, Long and Over (1973) extended the findings of Blakemore and Julesz to cover a wide range of adapting disparities. In their study, the adapting stereogram portrayed a surface containing a single square at one of a range of disparities with respect to the background. The test stereogram also contained a central square, and the disparity of the centre square could be altered until it appeared to lie in the same plane as the background and the whole surface appeared flat. Over a whole range of adapting disparities aftereffects of between 15 and 20 per cent were recorded. For example, it was found that after adapting to a square which had a disparity of 6 minutes of arc with respect to the background, the test surface appeared to be completely flat when the test square was actually at a disparity of 70 seconds arc with respect to the background. An effect of similar magnitude was observed by Mitchell and Baker (1973) who used stereoscopic line and grating stimuli rather than random dot patterns.

Since depth aftereffects can be generated with random dot stereograms the site of adaptation must be at the level of stereoscopic processing or beyond. Blakemore and Julesz (1971) suggest that the aftereffects are due to the adaptation of disparity processing mechanisms, perhaps of a similar type to those found physiologically (Barlow, Blakemore and Pettigrew, 1973; Poggio and Fischer, 1977). The demonstration that true depth aftereffects can occur for surfaces specified by binocular disparities, raises the question of whether depth aftereffects are also produced after prolonged viewing of depth surfaces specified by other sources of depth information. The experiments described here used the techniques described previously, to look at aftereffects following inspection of parallax depth surfaces. Aftereffects for depth from relative motion had not been previously reported in the literature. The aftereffects generated by motion parallax surfaces were also compared with those generated by stereoscopic surfaces.

5.2 Methods and procedure.

Depth aftereffects following prolonged inspection of sinusoidally corrugated depth surfaces were measured for both motion parallax and stereoscopic depth. The motion parallax and stereoscopic displays were identical to those described in the last chapter. In the motion parallax display, depth information was provided by introducing patterns of relative motion into a random dot pattern. The relative movement was linked to the movement of the observer, who moved from side to side on a chinrest while viewing the pattern monocularly. In the stereoscopic display, depth information was provided by binocular disparities between two random dot patterns which were viewed independently by the two eyes in the stereoscopic viewing arrangement. In both cases, the depth in the adapting surface was sinusoidally modulated so that the surface consisted of horizontal corrugations. In preliminary experiments, this corrugated surface seemed to produce a stronger aftereffect than surfaces containing square wave depth modulations or isolated areas in depth (although the latter were more similar to the stimuli used to measure stereoscopic aftereffects in previous experiments). The corrugated adapting surface had a spatial frequency of 0.1 cycles per degree throughout the experiment. This spatial frequency had been found to produce a large aftereffect which could easily be measured.

Depth aftereffects for both parallax and stereoscopic depth were measured using the same procedure. During an adapting period of several seconds the observer viewed the corrugated depth surface while tracking a moving point. This point moved from side to side, through about 4 degrees, along a horizontal line in the centre of the screen, midway between a peak and a trough of the corrugation (Figure 5.2a). Tracking prevented the build up of conventional afterimages during the inspection period, but ensured that any retinal region was stimulated by the same depth value throughout. After the adapting period, the corrugated adapting surface was replaced by a physically flat test surface which contained no relative motion or disparity and which would therefore have appeared flat to an unadapted observer. Initial observations indicated that after as little as 8 seconds adaptation, the flat test surface appeared to be corrugated in depth but with the direction of the corrugation of opposite sign to (180 degs out of phase with) the adapting corrugation (Figure 5.2b).

In order to measure the aftereffect a nulling procedure was used. It was found that the test surface could be made to appear flat if a physical depth corrugation, specified by relative motion or disparity, with the same phase as the adapting corrugation was introduced to cancel the depth aftereffect (Figure 5.2c). The amplitude of the depth corrugation that had to be introduced to null the aftereffect and make the test surface appear flat, could therefore be taken as a measure of the strength of the aftereffect. This task was chosen because it was

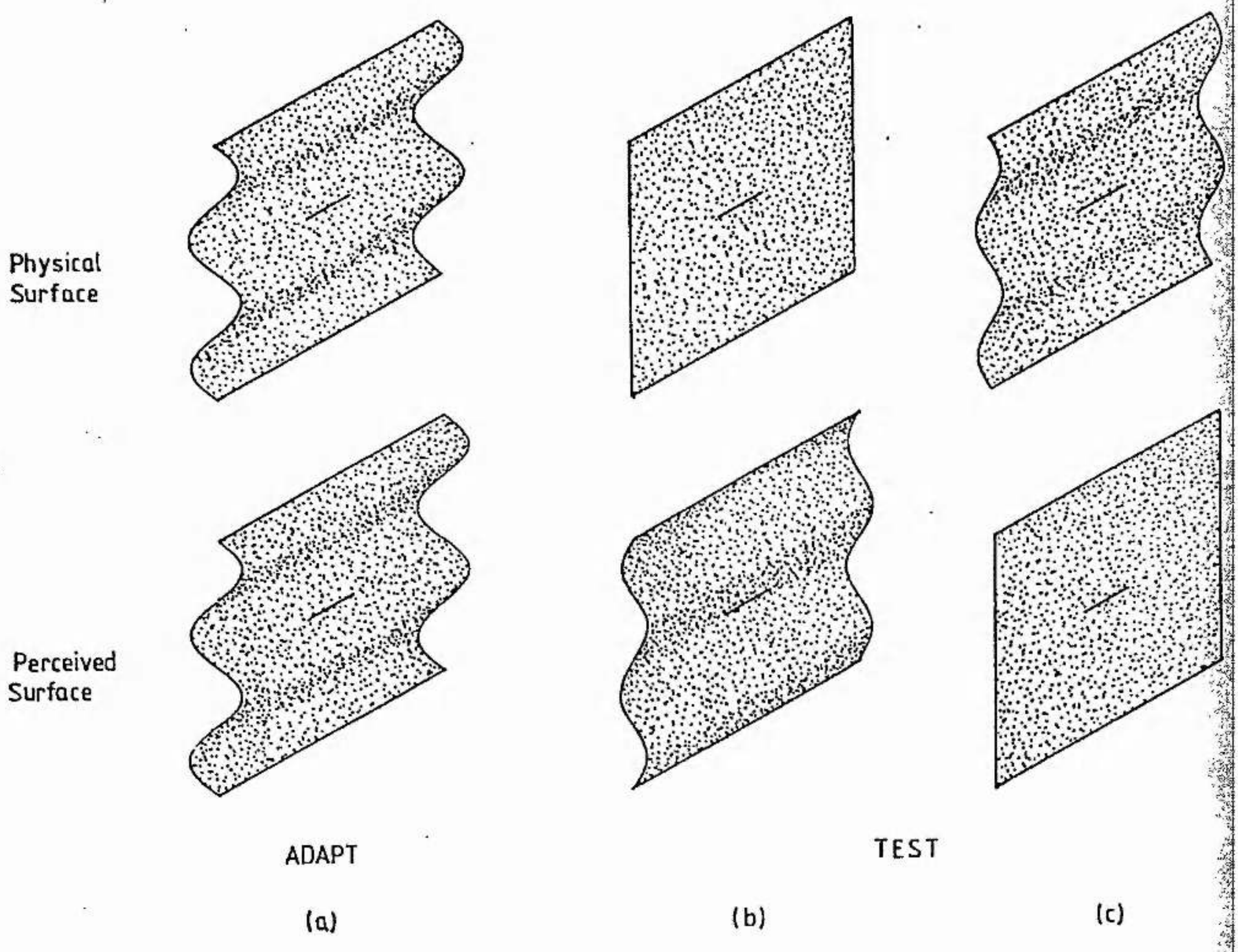


Figure 5.2.

To generate depth aftereffects, the observer viewed a corrugated adapting surface for several seconds while tracking a point moving along a horizontal line in the centre of the display (a). Following adaptation, a flat test surface appeared to be corrugated in depth with the opposite phase to that of the adapting surface (b). The observer nulled this aftereffect by "adding in" a physical depth corrugation to the test surface until it appeared flat.(c).

an easy, straightforward task for the observers and yielded a high level of consistency. The nulling procedure allowed the aftereffect to be measured quickly and easily in brief test periods. An alternative procedure would have been a matching task although this would have been rather more difficult for the observer. Moreover, a temporal matching procedure would have required a longer test period, whereas a spatial matching procedure would have required the use of a corrugated adapting surface of a relatively high spatial frequency.

Although depth aftereffects for both parallax and stereoscopic depth were observed after only a few seconds of adaptation, in order to measure the strength of the aftereffect, a topping-up procedure was used. Over a period of two minutes, observers were presented with continuous cycles of an 8 second presentation of the adapting surface, followed by a 1 second glimpse of the test surface. During each test period, observers were required to observe the appearance of the test surface and to judge whether it appeared to be corrugated in depth. They were then required to adjust a potentiometer, which controlled the amplitude of the depth corrugation present in the test surface, until the test surface appeared to be flat. In the case of the parallax display, the signal from the potentiometer altered the gain of the distortion signal, while in the stereoscopic display it altered the amplitude of the disparity signal, thus varying the overall amount of relative movement or disparity in the test surface. This manipulation did not affect the amount of relative movement or disparity in the adapting surface, which remained constant.

During the two minute trial observers adjusted the physical depth in the test surface so that by the end of the trial the test pattern looked as flat as possible. The amount of relative movement, for the parallax display, or the amount of disparity, for the stereo display, that the observer had introduced into the test surface to cancel the aftereffect was then recorded. This was expressed in units of equivalent disparity for parallax, or disparity for stereo, and the percentage strength of the aftereffect was also determined. That is, the amount of disparity in the test surface at the null setting was also expressed as a percentage of the amount of disparity in the adapting surface.

Six subjects took part in the initial experiment, four of whom were naive as to the purpose of the experiment. Depth aftereffects were measured following inspection of both parallax and stereoscopic surfaces. In both cases the spatial frequency of the adapting corrugation was 0.1 cyc/deg and the amount of peak to trough depth in the parallax corrugation was equivalent to 4.75 min arc disparity, while the peak to trough depth in the stereo corrugation was 10 min arc. Each observer made four settings for both parallax and stereo, with an interval of at least fifteen minutes between each setting so that any aftereffect from the previous trial had dissipated. The mean value of these settings was taken as a measure of the strength of the aftereffect for each subject.

In addition, two subjects repeated the measurements for several different adapting disparities. Equivalent disparities of 2.25, 4.75 and 9 min arc were used for the parallax display and five settings were made at each disparity. For the stereo display, adapting disparities of 2.5, 5, 10 and 20 min arc were used and two settings were made at each disparity.

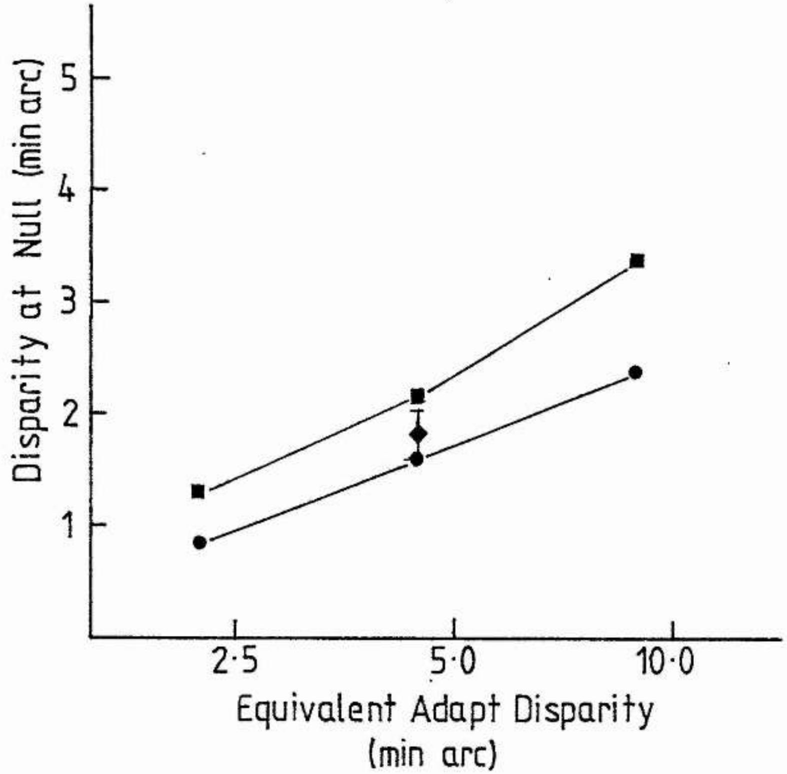
5.3 Results.

Strong negative depth aftereffects occurred after prolonged viewing of depth surfaces. They occurred both when depth was specified by motion parallax information and when it was specified by binocular disparities. In preliminary experiments, aftereffects were found after viewing corrugated adapting surfaces over a wide range of depth spatial frequencies and disparities. In all cases, following adaptation to a corrugated depth surface, a subsequently viewed, physically flat test surface, appeared to be corrugated in depth but with the corrugations opposite in sign to (180deg out of phase with) those of the adapting surface. The build-up of the aftereffect was rapid, with a noticeable effect being present after a single adapting period of only 8 seconds. The aftereffect was fully developed after two minutes of adaptation and, in the test phase, its strength declined rapidly so that it was markedly reduced after viewing a flat test surface for several seconds.

An important observation was that the aftereffects could be produced by prolonged viewing of motion parallax depth surfaces, both when the observer moved from side to side while viewing the test surface, and when the observer remained stationary during the test period. It was, of course, not possible to null the aftereffect in the latter case and so a comparison between the strengths of the effects in each case could not be made. Subjectively, however, there did not appear to be any difference in the size or the saliency of the aftereffect when the observer remained stationary during the test period.

In the main part of the experiment, observers were required to null or cancel the aftereffect by varying the amplitude of the depth corrugation present in the test surface. In general, observers found this task straightforward and had no difficulty in adjusting the depth in the test surface to find a point where it appeared flat. They rarely required more than the two minute period to reach a satisfactory setting. When the mean of these null settings was taken as a measure of the strength of the aftereffect, it was found that there were large aftereffects for all subjects for motion parallax depth surfaces. The strengths of these aftereffects were comparable to those found for stereoscopic surfaces.

The strengths of the motion parallax aftereffects are shown in Figure 5.3. On the left, the amount of peak to trough relative motion in the test surface at the null point, is expressed in units of sec arc equivalent disparity and plotted as a function of the peak to trough equivalent disparity of the adapting surface. The filled lines show individual data for two observers and the diamond indicates the mean strength of the aftereffect for six observers, after adapting to a surface containing 4.75 min arc equivalent disparity. For an adapting surface of this disparity, large aftereffects were obtained where the mean amount of equivalent disparity needed to cancel the aftereffect, was about 1.8 min arc. On the right of the figure, the amount of equivalent disparity needed to null the aftereffect is expressed as a percentage of the equivalent disparity of the adapting surface. When expressed in this way, it can be seen that the mean aftereffect was just over 40%. Between observers the strength of the aftereffect ranged from 35% to 48%. Looking at the individual subject data it is apparent that, as the peak to trough relative motion (equivalent disparity) in the adapting surface increased, the amount of parallax



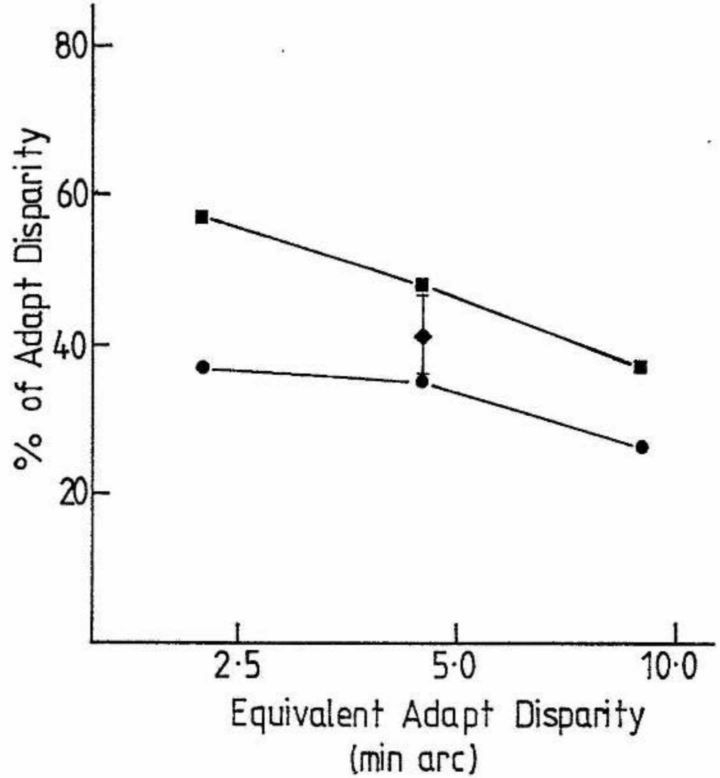


Figure 5.3.

Aftereffects of parallax depth : (a) The amount of peak to trough equivalent disparity that had to be "added in" to the test surface to cancel the negative aftereffect is shown as a function of the peak to trough disparity of the adapting surface for two observers BJR (■) and MEG (●). The mean strength of the aftereffect for six observers at an adapting disparity of 4.75 min. arc is also shown (◆).
(b) The same data have been replotted to show the percentage strength of the aftereffect, that is, the percentage of the disparity in the adapting surface that was needed to null the aftereffect.

depth that had to be added in to the test surface also increased (Figure 5.3a). However, in percentage terms, the strength of the aftereffect decreased with increasing equivalent adapting disparity (Figure 5.3b).

The comparison data measured for stereoscopic depth are shown in Figure 5.4 and a similar pattern of results is observed. The mean strength of the aftereffect for six subjects, shown by the diamond, was around 5 min arc for a 10 min arc adapting disparity, that is, 5 min arc of disparity had to be added in to the test surface to cancel the aftereffect. On the right the data are plotted in percentage terms and the mean strength of the aftereffect is about 50%. There was quite a large variation in the size of the aftereffect among individual observers, so that the strength varied from 40 to 75% across observers. Looking at the data for two experienced observers, in absolute terms the amount of disparity needed to cancel the aftereffect increased with the disparity of the adapting surface, (Figure 5.4a), but the percentage effect decreased with increasing adapting disparity (Figure 5.4b).

5.4 Discussion.

i) Aftereffects for motion parallax depth

The results found in the present experiment clearly demonstrate that large depth aftereffects can be produced after inspection of depth surfaces, where motion parallax is the only source of depth information. They, therefore, provide the first demonstration that a true depth aftereffect can be produced using a depth source other than

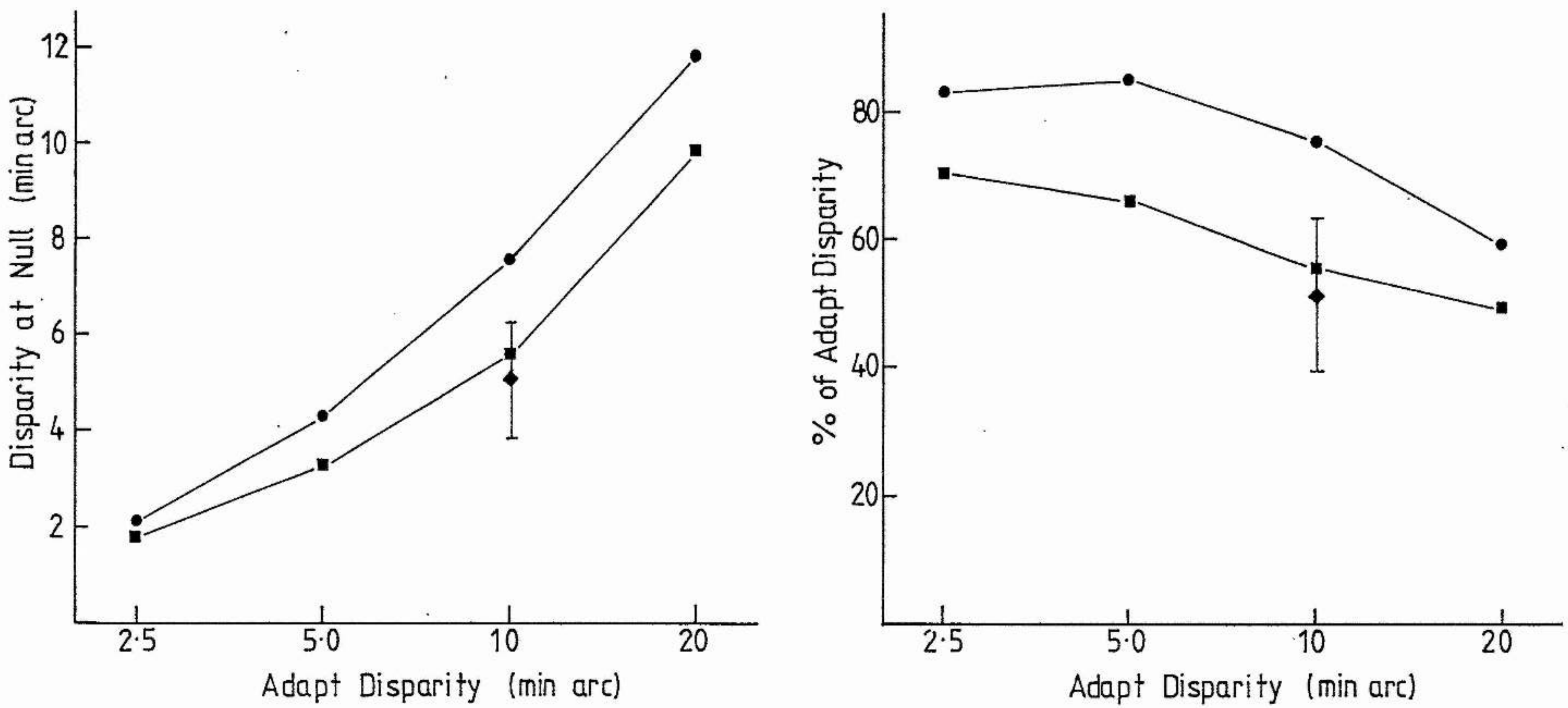


Figure 5.4.

Aftereffects of stereoscopic depth: (a) The amount of peak to trough disparity that had to be "added in" to the test surface to null the negative aftereffect is shown as a function of the disparity of the adapting surface. (b) The data have been replotted to show the strength of the aftereffect as a percentage of the adapting disparity. In both cases the mean data for six observers (◆) and individual observer data for BJR (■) and MEG (●) are plotted.

stereopsis (Graham and Rogers, 1982a). By analogy with arguments made for other visual dimensions (Blakemore and Sutton, 1969; Mollon, 1974; Frisby, 1979) the results found here suggest that there are specific mechanisms for processing motion parallax information within the human visual system and that these mechanisms can be adapted. The parallax depth aftereffect is a negative aftereffect since the phase of the apparent corrugation in the test surface is opposite, or complementary to, the phase of the adapting corrugation. The aftereffect is also phase-specific. When the observer is asked to scan the depth surface during the adapting period, rather than track the horizontally moving spot, no aftereffect is produced. The aftereffect therefore requires any particular region of the retina to be stimulated by an area at the <u>same</u> depth value throughout the adapting period.

It has been assumed, in recent theories of visual processing, that different sensory attributes, such as colour, movement, spatial frequency and disparity, are initially processed relatively independently. Within each of these dimensions, processing involves a number of separate "channels" which are tuned to different but overlapping ranges of stimulus values along that dimension. The perceived value at any time is thought to depend either on the particular channel giving the maximum response or, more likely, on the overall response distribution among the different channels. (For example, see the theories outlined by Coltheart, 1971; Braddick et al., 1978; Frisby, 1979; Marr, 1982.) Prolonged stimulation by a particular stimulus value along a sensory dimension, is thought to produce some reduction of response which is termed adaptation. This reduction affects only channels responding to the particular stimulus value and hence alters the subsequent response distribution of channels within that sensory dimension (Figure 5.5a). This model predicts that, following adaptation, several perceptual changes should be expected to occur. Firstly, the strength of the perceptual sensation should decline during adaptation, and secondly, after adaptation, thresholds for stimuli handled by the adapted channels should be higher than in the unadapted state. Finally, as illustrated in Figure 5.5a, the perceived values of stimuli within the same dimension and close to the adapting stimulus should be shifted or displaced along that dimension, away from their true values (Blakemore and Sutton 1969; Anstis, 1975).

Negative aftereffects, such as those that occur for colour and motion, where, after adaptation, a neutral stimulus appears to have complementary characteristics to those of the adapting stimulus, are thought to arise from an "opponent" organisation between channels. It is assumed that the channels are organised in opponent pairs and that the perceived attribute depends on the balance of activity between the two channels. Adaptation is thought to upset the balance between the paired channels, through fatigue or inhibition, so that a complementary percept arises when a neutral stimulus is subsequently presented (Sutherland, 1961; Favreau and Corballis, 1976). More recently, the negative movement aftereffect has also been attributed to a change in the overall response distribution of channels tuned to different directions of movement, without needing to postulate an opponent organisation of these channels (Mather and Moulden, 1980; Levinson and Sekuler, 1980). In this model, the perceived direction of motion of a stimulus depends on the weighted mean response among channels broadly tuned to different directions of motion. Following adaptation to one direction the response to this and neighbouring directions is reduced so that the weighted average of the total distribution is in a

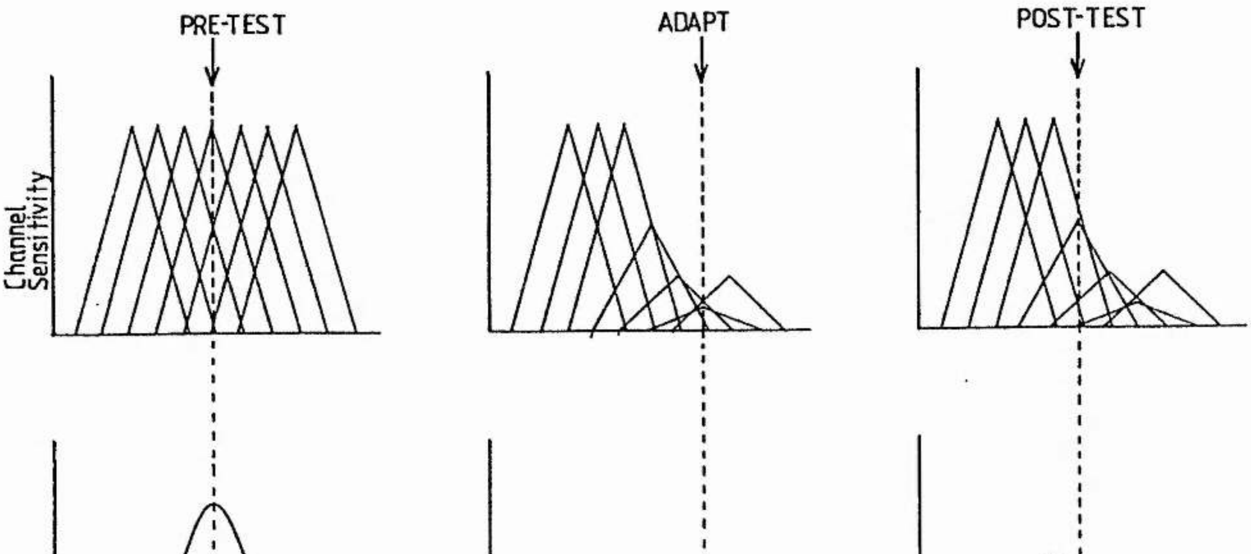


Figure 5.5.

(a) The upper row of graphs represent the sensitivities of a set of overlapping channels along a sensory dimension. The lower set of graphs represent the distribution of activity in these channels produced by the stimulus value indicated by the arrow. A point on the abscissa corresponds to the channel centred on a particular value along the stimulus dimension. The left panel shows the response of the system in an unadapted state where the perceived value is assumed to be that of the most active channel. The centre panel shows the effect of adapting the system to a higher stimulus value. The adaptation is assumed to depress the sensitivity of each channel by an amount depending on how strongly it is stimulated. On the right the response of the system to the original stimulus value is shown after adaptation. The distribution of activity is skewed since channels centred at higher stimulus values are more adapted than those centred at lower stimulus values.

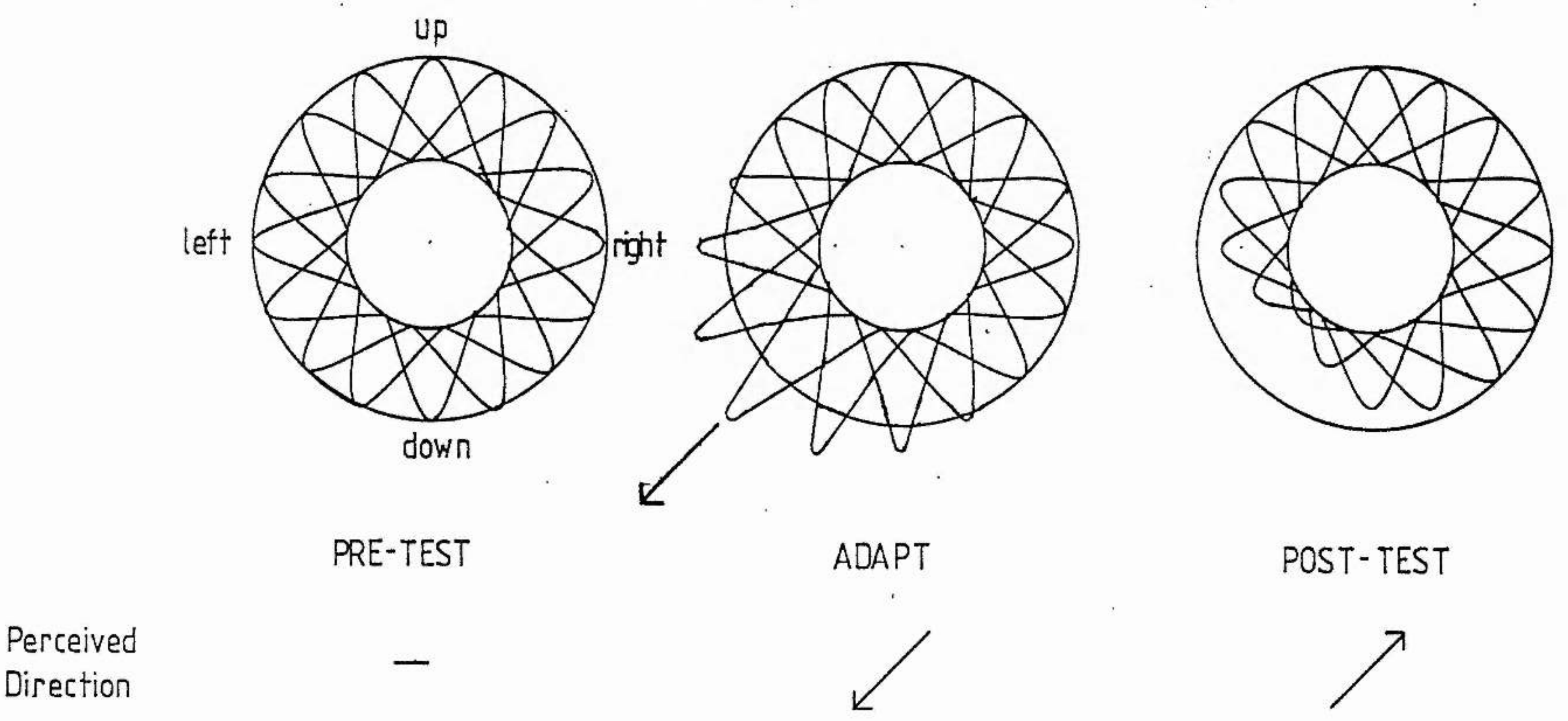


Figure 5.5b.

The negative movement aftereffect can be explained as a result of a shift in the distibution of activity within different channels. The motion system is assumed to consist of a set of movement sensitive channels which are optimally tuned to different directions of movement. The balance between these channels determines the perceived direction of movement. In the abscence of adaptation a stationary surface will be perceived veridically, as all channels are responding equally (left). During adaptation channels sensitive to the adapting direction will be heavily stimulated (middle) and will gradually become less sensitive. Subsequently, in the presence of a stationary pattern the distribution of activity will be depressed in the region of the adapting direction (right) and the weighted average of the total distribution would yield a direction opposite to the adapting direction. If the amount of skew following adaptation is sufficient to produce a movement signal, the stationary test surface will be perceived as moving in the opposite direction to the adapting surface.

direction opposite to the adapting direction (see Figure 5.5b). Although this model can be applied to movement aftereffects it is not appropriate for other kinds of negative aftereffect. In the case of colour, for example, the different color channels respond to different ranges of wavelength varying from low to high. A weighted average among these channels after adaptation would not produce a response of the complementary colour to the adapting stimulus. For colour therefore an opponent organisation at a higher level must be postulated to explain negative colour aftereffects.

Within this general theoretical framework, the presence of large negative aftereffects for depth surfaces specified by motion parallax information, leads to the question of the type of perceptual channel or mechanism responsible for the parallax aftereffect. There are several possible levels at which the aftereffect might arise. The first hypothesis might be that the parallax depth aftereffect is a result of adaptation within movement processing mechanisms. There is some well established physiological and psychophysical evidence that velocity-sensitive mechanisms exist in the visual system (Sekuler, 1975; Richards, 1971b), and that these mechanisms are directionally selective since they produce direction specific aftereffects (Sekuler and Ganz, 1963; Pantle and Sekuler, 1969; Movshon, 1975). It is quite clear, however, that the present depth aftereffect does not result from adaptation at this level. This is because each region of the retina is stimulated by opposite directions of motion as the observer moves from side to side while viewing the adapting surface. Hence, there cannot be any resultant movement aftereffect at any individual point. A second possibility is that the aftereffect is an example of a contingent movement aftereffect. Contingent aftereffects (McCullough,

1965) have been demonstrated for movement and colour (Mayhew and Anstis, 1972) and for movement and disparity (Anstis and Harris, 1974). A movement aftereffect contingent on the direction of the observer's gaze has also been found by Mayhew (1973). A possible hypothesis, therefore, is that the parallax depth aftereffect is an example of a movement aftereffect contingent on the direction of observer motion, since, for any retinal region, the direction of motion depends on the direction in which the observer is moving. This possibility can be ruled out, however, by the observation that the aftereffect is still present when the observer remains stationary while viewing the test surface.

So far, it has been assumed that the motion of each individual part of the visual field is initially processed independently. However, many of the mathematical analyses described in the second chapter have suggested that mechanisms which responded to relative movement between neighbouring parts of the visual field, would be more appropriate mechanisms for extracting depth from motion (Longuet-Higgins and Prazdny, 1980; Clocksin, 1980b). Physiological evidence for the existence of neurons sensitive to relative motion within their receptive field has now been established (Burns, Gassanov and Webb, 1972; Frost, 1978; Frost et al., 1981; Allman et al., 1982) and it is possible that such mechanisms are being adapted here. However, as the formal models point out, in order to perceive an unambiguous depth surface from motion parallax information, the pattern of relative motion has to be interpreted in terms of the overall direction of translation. This is because, within a limited retinal area, the same motion transformation would be produced by a corrugated surface of one phase accompanied by translation in one direction or by a corrugated surface of the opposite phase accompanied by translation in the opposite direction. Disambiguating information about the direction of translation may be obtained from extra-retinal sources such as vestibular input about eye or head movements. It can also be obtained visually, in either active or passive parallax situations, from the relative movement of the surface with respect to its background. In either case, since an unambiguous depth surface must be perceived during the inspection period for adaptation to occur, the parallax depth aftereffect demonstrated here, must occur at or beyond the level at which the motion transformation has been disambiguated. That is, after depth information has been extracted from the pattern of relative motion.

ii) Stereoscopic Aftereffects

The present study also found strong, negative depth aftereffects after adaptation to depth surfaces specified stereoscopically, and these stereoscopic aftereffects were similar in size to the aftereffects found after inspection of parallax surfaces (Graham and Rogers, 1982a). After inspection of a stereoscopic corrugation, a subsequently viewed, flat test surface appeared to be corrugated in depth with the opposite phase to that of the adapting corrugation. The size of the stereo aftereffects found here, were large, the strength of the aftereffect varied from 40% to 75% for different conditions and observers. The finding of stereo aftereffects confirms the results of the previous studies showing that adaptation to binocular disparity produces negative aftereffects. The aftereffects found in the present study are, however, larger than those reported in previous studies where the largest aftereffect measured was around 25% (Blakemore and Julesz, 1971). A possible reason for this difference could have been the use of corrugated adapting surfaces which were continuously modulated in depth. The adapting stimuli used in previous studies had consisted of squares standing out in depth, and therefore contained only two or three different disparity values. In the luminance domain it has been found that square shaped luminance gratings produce weaker afterimages than sinusoidal gratings (Georgeson and Turner, 1982). In the present experiment, informal observations have suggested that continuous depth surfaces produce more compelling aftereffects than discrete depth planes. Another possible reason for the large effects found in the present study is the use of a "topping-up" procedure, where cycles of adapt and test were used to measure the strength of the aftereffect. This procedure allowed the aftereffect to build up over time with little decay or dissipation during the brief test period. Preliminary data suggested that the aftereffect declined fairly rapidly over a few seconds and previous studies may have underestimated the size of the aftereffect due to this rapid decay.

In line with the reasoning outlined above, the stereoscopic depth aftereffects found in previous studies have been interpreted as a result of the adaptation of disparity processing mechanisms. The existence of disparity processing mechanisms which are tuned to different ranges of disparity values, has been suggested psychophysically (Blakemore and Hague,1972) and found physiologically in the cat and monkey (Barlow, Blakemore and Pettigrew, 1967; Pettigrew, 1973; Poggio and Fischer, 1977). It has been assumed that the depth aftereffect arises from a shift in the response distribution among channels tuned to different ranges of disparity values in accordance with the model described in Figure 5.5a. For example, prolonged viewing of a square at a disparity of 6 min arc in front of a background, is assumed to alter the subsequent response distribution for a zero disparity test square, so that it is perceived at a disparity of perhaps 2 min arc behind the background.

The type of model illustrated in Figure 5.5a, predicts that, above a certain small value, the greater the "distance" between adapt and test values, the smaller the amount of perceptual distortion. Such a relationship has indeed been found for the orientation and spatial frequency of luminance gratings (Ware and Mitchell, 1974; Blakemore, Nachmias and Sutton, 1970). Although such a model seems feasible for the aftereffects obtained using discrete depth values in the adapting surface, it is difficult to see how it could account for the nature of the negative aftereffects found here. For example, additional observations showed that for a corrugated stereoscopic surface, where the trough of the corrugation was at a disparity of zero min arc and the peak at 10 min arc, a strong negative aftereffect was observed. For a zero disparity test surface, the largest shift in perceived disparity occurred for the part of the surface which had corresponded to the peak of the adapting surface, and which appeared as a trough in the test surface. Areas which were at a lesser disparity in the adapting surface were perceived at a lesser disparity in the test, that is, areas which originally had a disparity close to zero showed less of a shift in perceived disparity than those which originally had a disparity farther from zero. It was also found that the strength of the aftereffect was greater in absolute terms for larger adapting disparities. Both these findings are contrary to that predicted by the above model which assumes a number of channels tuned to different ranges along the disparity dimension.

Another possibility is that the negative aftereffect results from an opponent organisation between crossed and uncrossed disparity channels. Pools of uncrossed and crossed disparity units have been postulated from other studies (Richards, 1971), but as yet there is no physiological evidence for an opponent organisation between them. An opponent organisation of this sort would, however, also have difficulty in explaining the greater distortions found at larger adapting disparities. It would be necessary that the opponent organisation existed between channels tuned, at least crudely, to the same range of disparity. This would ensure that a larger crossed adapting disparity produced an aftereffect at a larger uncrossed disparity.

Another informal observation, indicates that an emphasis on the magnitudes of the disparity values in the adapting and test surface might be misleading in any attempt to explain the stereo aftereffect. In the experiment described above, the adapting surface was displayed so that the fixation line lay in the plane of the screen at zero disparity. A peak and a trough of the corrugation were therefore at crossed and uncrossed disparities, respectively, of the same amount. The test surface was initially a flat zero disparity surface in the plane of the screen. If however, with the same adapting surface, a flat test surface was presented at a crossed or uncrossed disparity, a depth aftereffect was still observed. The surface appeared corrugated in depth and the effect was indistinguishable from that obtained with a zero disparity test surface. This observation needs to be rigorously investigated and the strength of the aftereffect measured for test surfaces at different disparities. If further study confirms the original observation, then it strongly suggests that the aftereffect depends on the __spatial distribution__ of disparities, that is the relative disparities between neighbouring areas, in the adapting surface, rather than on the magnitudes of crossed or uncrossed disparities at individual points.

This suggests a third possibility for the site of the stereoscopic aftereffect. Rather than being located among mechanisms which extract the disparity values of different points in the image, the aftereffects might result from the adaptation of mechanisms designed to extract information about relative disparity between neighbouring areas. These mechanisms would perhaps be similar to the convexity mechanisms suggested by Nakayama and Loomis (1974), or the shear detectors suggested by Longuet-Higgins and Prazdny (1980), for the extraction of velocity gradients over space. It was suggested above that such mechanisms are likely to be involved in the processing of parallax depth. Mechanisms of a similar kind must also exist in the stereoscopic system since it is necessary to know how the depth values within the image change over space, in order to be able to perceive the three-dimensional form of an object or surface. Mechanisms designed to register the change of disparity over space, or disparity gradients, would be a possible basis for this process and if such mechanisms were adaptable, they might easily produce the kind of stereo aftereffects found in the present study. If adaptation resulted in some imbalance in the opponent organisation among these disparity gradient mechanisms, or a change in the overall response distribution of mechanisms tuned to different depth gradients, then negative depth aftereffects would be expected to occur.

iii) Similarities between depth aftereffects

The empirical characteristics of aftereffects produced by inspection of a parallax depth surface were similar to the aftereffects found for stereoscopic surfaces. The magnitude of the aftereffect was of the same order in both cases although, on average, the parallax aftereffect was slightly lower. Moreover, the relationship between the size of the aftereffect and peak to trough disparity of the adapting corrugation was very similar for adapting diaprities of 10 min arc and below. Adapting surfaces with more than 10 min arc of equivalent disparity were not used to measure parallax aftereffects because, at these amplitudes, relative motion begins to be perceived in the surface.

The possibility that aftereffects arise from the adaptation of relative disparity detectors, perhaps points to a link between the depth aftereffects found for parallax surfaces and those that occur for stereoscopic surfaces. This may account for the observed empirical similarities. As mentioned above, it is likely that parallax information is extracted by mechanisms which respond to relative motion or change in velocity over space. When disambiguated by knowledge of the overall direction of translation, such mechanisms respond to changes in depth over space, that is, relative depth specified by differential velocities. If the parallax depth aftereffect results from the adaptation of these mechanisms, and the stereo aftereffect from the adaptation of mechanisms which respond to relative disparity, then a similar explanation can be advanced to explain the two effects. In general, both depth aftereffects could arise from the adaptation of mechanisms designed to pick up information about changes in depth over space, in the one case specified by differential motion, in the other by differential disparity, between different retinal areas. Such mechanisms could be the building blocks for the depth processing systems which allow us to perceive the three-dimensional structure of depth surfaces in our environment.

5.5 Further experiments on depth aftereffects.

i) Depth aftereffects as a function of corrugation frequency

The parallax and stereo depth aftereffects found in the previous experiment, were measured after adapting to a corrugated depth surface with a spatial frequency of 0.1 cyc/deg. This depth spatial frequency had, informally, seemed to provide a large aftereffect which was easy to measure using the nulling technique. However, the exact nature of the relationship between the depth spatial frequency of the adapting surface and the strength of the depth aftereffect, had not been determined. A further study was therefore carried out to measure aftereffects for adapting corrugations with varying spatial frequencies.

The strength of the aftereffect was measured, in the same way as before, using a nulling technique. During a two minute period which consisted of cycles of 8secs adaptation followed by a 1 second presentation of the test surface, the observer adjusted the peak to trough depth in the test corrugation until the aftereffect had been cancelled and the test surface appeared flat. The spatial frequency of the corrugated test surface was always the same as that of the adapting surface. Aftereffects were measured for corrugated adapting surfaces of ten different spatial frequencies for stereoscopic depth (0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 cycles per degree), and four settings were made at each spatial frequency. For parallax depth, aftereffects were measured at five spatial frequencies (0.05, 0.1, 0.2, 0.4 and 0.8 cycles per degree), and two settings were made at each frequency. For stereo surfaces the peak to trough depth in the adapting surface was 8 min arc disparity, for all frequencies, and for parallax surfaces the equivalent adapting disparity was 8 min arc.

The strengths of the depth aftereffects obtained for corrugated adapting surfaces of different spatial frequencies are shown in Figure 5.6. The strength of the aftereffect is plotted in percentage terms so that the amount of peak to trough depth, that had to be added in to the test surface to cancel the aftereffect, is expressed as a percentage of the peak to trough depth in the adapting surface. For stereoscopic adapting surfaces, the strength of the aftereffect was just over 50% at the lower spatial frequencies and remained roughly constant until the adapting spatial frequency reached 0.4 cyc/deg when it began to decrease. It was also found that, for adapting surfaces specified by parallax depth information, the aftereffect was somewhat lower at around 30% for this observer. A similar difference in the size of the two depth aftereffects had been found for this observer in the previous study. For parallax surfaces, the size of the aftereffect again remained fairly constant as the frequency of the adapting surface increased up to 0.4 cyc/deg, although there was a slight fall off by 0.4 cyc/deg and a substantial decrease by 0.8 cyc/deg. Depth aftereffects could not be measured for parallax depth surfaces with spatial frequencies above 0.8 cyc/deg as it was found that it was impossible to perceive a stable aftereffect in these cases. This may

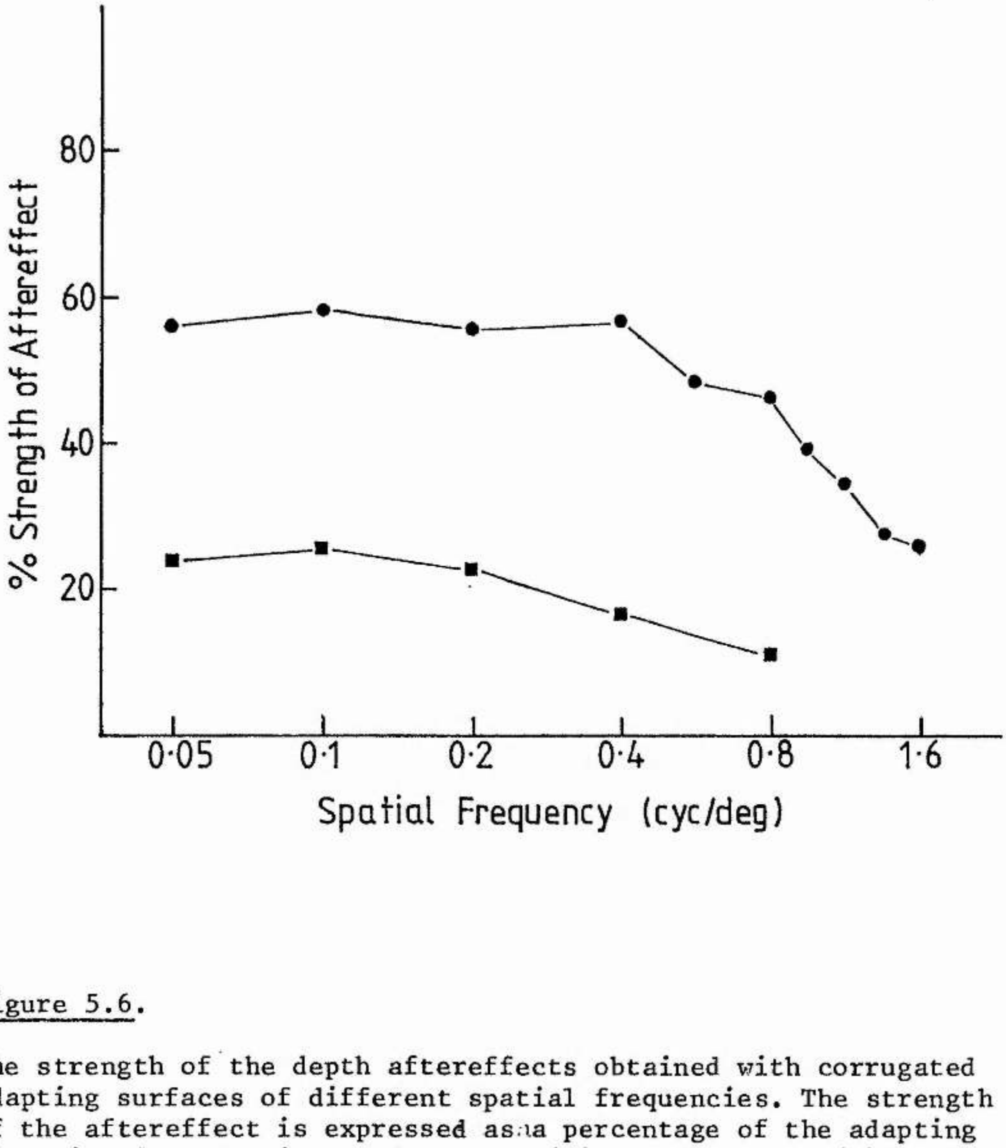


Figure 5.6.

The strength of the depth aftereffects obtained with corrugated adapting surfaces of different spatial frequencies. The strength of the aftereffect is expressed as a percentage of the adapting disparity for adapting surfaces specified by parallax (■) and stereoscopic (●) depth information. (Observer MEG).

have been due to the greater difficulty in maintaining vertical fixation between a peak and a trough at these higher frequencies, a problem which is more apparent for parallax than stereo as the observer has to move from side to side while viewing the parallax adapting surface.

The results found in this study show that the parallax and stereo depth aftereffects, obtained after viewing corrugated adapting surfaces, do not depend crucially on the spatial frequency of the adapting corrugation. The strength of the aftereffect does, however, decrease at frequencies above 0.8 cyc/deg and at these frequencies the perceived aftereffect becomes less stable and more difficult to measure especially for parallax depth surfaces. The decrease in the aftereffect at higher spatial frequencies might be thought to be due to the fact that the threshold for detecting corrugated surface at these spatial frequencies starts to rise. Hence, the amplitude of the adapting corrugation relative to threshold would be less for these frequencies. However, no decline in the strength of the aftereffect occurred at the low spatial frequencies of 0.05 or 0.1 cyc/deg, where detection thresholds are also high. In addition, the previous study indicated that the percentage size of the aftereffect actually increased for adapting surfaceswith <u>less</u> peak to trough depth.

The present results also suggest that depth surfaces which contain high frequency depth information, for example, surfaces containing sharp depth changes, will not produce aftereffects as strong as those containing low frequency, gradual depth change. This may be one reason why the initial findings of Blakemore and Julesz (1971), and others, on stereoscopic aftereffects, found depth aftereffects which were smaller than those found in the present experiments. These studies used adapting surfaces containing small squares standing in discrete depth planes rather than the continuous depth surfaces used here.

In the present experiments, it was found that the size of the depth aftereffect increased in absolute terms, but decreased in percentage terms, as the peak to trough depth of the adapting surface was increased. Since the adapting surfaces were sinusoidal depth corrugations this relationship could have been due to two factors which change together as the depth amplitude of the corrugation increases, namely, the absolute depth difference between a peak and a trough of the surface, and the maximum degree of depth slope in the surface. The experiment just described has shown that there is very little change in the strength of the aftereffect for corrugated adapting surfaces over a range of spatial frequencies, despite the fact that the degree of depth slope present in the surface varies widely for corrugations with frequencies within this range. This suggests that the original finding of an increase in the strength of the aftereffect with increasing adapting amplitude, can be attributed to the increase in the relative depth between the peak and the trough of the corrugation rather than to the increased gradient of depth change within the surface. However, it is also possible that the strength of the aftereffect remains roughly constant over a range of adapting spatial frequencies, because of an interaction between the gradient of depth change and the spatial area over which this depth change occurs. In this case, although at lower spatial frequencies the decreased gradient might be expected to lead to a weaker aftereffect, the depth change occurs over a larger area thus allowing for greater spatial integration.

In a study of movement aftereffects following inspection of differentially moving random dot patterns, Nakayama and Tyler (1981a) have found results similar to those reported here. The stimuli were moving random dot patterns where the velocity of each row varied sinusoidally from the top to the bottom of the surface and were similar to those used in their previous study which was described in the last chapter (Nakayama and Tyler, 1981b). They showed that the strength of the movement aftereffect remained constant until the frequency of the sinusoidal velocity signal increased above 1 cycle per degree. Above this value the strength of the aftereffect decreased rapidly and the decrease could not be attributed to poor eye fixation. They attributed this aftereffect to the adaptation of mechanisms designed to detect relative motion. The similarity between this differential movement aftereffect as a function of spatial frequency and the parallax depth aftereffect found here suggests that they may arise from similar mechanisms.

ii) Other types of depth aftereffect

The depth aftereffects reported above, which occur following inspection of both parallax and stereoscopic depth surfaces, are negative depth aftereffects. After adaptation, the neutral test stimulus is perceived to have a complementary three-dimensional structure to that of the adapting surface. Such an aftereffect is analogous to the waterfall illusion in the movement domain and to the afterimages found for colour and brightness. The negative aftereffects found for corrugated depth surfaces can, in fact, be considered to be a type of depth afterimage. The presence of the aftereffect depends crucially on maintaining vertical fixation, while viewing the horizontally-oriented corrugations in the adapting surface. If the eyes are allowed to scan freely, any area of the retina is stimulated by many different depth values and no negative aftereffect is observed on subsequent viewing of a flat test surface. This is again analogous to afterimages of brightness and colour, which also rely on steady fixation. In this respect, this type of aftereffect is phase-specific as it depends on the depth structure maintaining a constant position, with respect to the retina, throughout the adapting period.

It was mentioned earlier that a model of visual processing which involves separate channels tuned to different ranges of stimulus values along a stimulus dimension (Figure 5.5a), predicts that other perceptual effects should follow adaptation, in addition to any negative aftereffect which might occur. Firstly, such a model predicts that if adaptation produces a reduction in the response of channels which respond to the adapting stimulus, then, during the adapting period, the strength of the perceived stimulus attribute should weaken. For example, it has been found that during adaptation to a moving grating, its perceived velocity decreases (Wohlgemuth, 1911; Gibson, 1937). An analogous effect also occurs in the depth domain. After viewing a corrugated adapting surface for a minute or so the amount of peak to trough depth, or depth contrast, appears to decrease so that the corrugations appear shallower. The effect again depends on maintaining vertical fixation throughout the adapting period, and so is phase-specific.

The second predicted effect of prolonged stimulation is a raised threshold for subsequently presented stimuli which are handled by the adapted channels. This type of adaptation effect is known as threshold elevation and the investigation of this effect in the movement and spatial frequency domain has produced useful information about the underlying processing mechanisms (Pantle and Sekuler 1968; Blakemore and Campbell, 1969). Contrast threshold elevation has, for example, been found for luminance gratings, where prolonged viewing of a grating of one spatial frequency raises subsequent thresholds for gratings of similar spatial frequencies. By measuring the extent of threshold elevation for gratings over the whole range of spatial frequencies, it has been found that the maximum elevation occurs for test frequencies which are the same as the adapting frequency, and elevation decreases to zero for test gratings that differ from the adapting grating by more than one octave in frequency. This type of data allows estimates for the bandwidths of the adapted channels to be calculated. Contrast threshold elevation effects for luminance are phase <u>independent</u>, since, in order to avoid brightness afterimages, the luminance grating is scanned in a direction orthogonal to the contours of the grating during the adapting period.

In the depth domain, the present experiments showed that strong negative aftereffects occurred after adaptation. It was not possible, therefore, to measure any phase-dependent threshold elevation. In a sense, however, the negative aftereffect does show that threshold elevation of this kind must have occurred. After adaptation, at the null setting where the test surface appears flat, there is actually a depth corrugation present in the test surface which would be well above threshold in the unadapted state. However, in addition to the negative depth aftereffect, it is also possible that there is a phase-independent threshold elevation effect, analogous to the contrast threshold elevation found in the luminance domain.

Such a possibilty has been investigated for stereoscopic depth in a recent paper by Schumer and Ganz (1979). The inspection stimuli were stereoscopic depth surfaces, sinusoidally modulated in depth, which were similar to the disparity gratings used in the present experiments. The threshold depth amplitudes, for test disparity gratings of varying spatial frequencies, were measured following prolonged inspection of an adapting disparity grating at a fixed spatial frequency. These thresholds were compared with thresholds obtained for the same stimuli prior to adaptation. During the adapting period, observers scanned the horizontally oriented disparity gratings in a vertical direction, across the depth contours, thus preventing the build-up of phase-dependent negative disparity aftereffects. Schumer and Ganz found that, after adaptation, threshold elevation occured for test gratings over a range of depth spatial frequencies, with the maximum elevation, of about 50%, occurring for test gratings of the same spatial frequency as the adapting grating. Threshold elevation gradually fell off as the frequency difference between adapt and test increased. In detail, they found that, for an adapting frequency of around 1.5 cyc/deg, there was no threshold elevation for test gratings of below 0.4 or above 4.0 cyc/deg, and for a 0.5 cyc/deg adapting grating no elevation occurred for corrugations above 2 cyc/deg.

Schumer and Ganz interpret these results as evidence for separate mechanisms within the disparity processing system which respond to different frequencies of disparity modulation over space. Support for such a model is also provided by another experiment reported in the same paper which uses subthreshold summation procedures, first used for luminance gratings by Graham and Nachmias (1971). Thresholds were measured for corrugated disparity surfaces of different spatial frequencies and these were compared with those for more complex depth surfaces, which consisted of the sum of two disparity corrugations of different spatial frequencies. The amplitude of one of the components of the compound depth surface was kept constant at some value below threshold and the threshold for the compound was compared with the threshold for the simple corrugation with the same spatial frequency as the other component. Schumer and Ganz found that the threshold was the same for both the simple and compound depth gratings, despite the presence of a subthreshold component at a different spatial frequency in the compound. They interpret this finding to mean that the two component depth spatial frequencies are detected by separate independent disparity mechanisms.

The presence of phase-independent threshold elevation argues strongly for the existence of depth processing mechanisms which respond to depth modulation of a particular frequency irrespective of the position of the depth contours within the retinal area served by each mechanism. Since such a finding is important for theories of depth processing in general, it was decided to investigate the existence of threshold elevation effects for parallax depth surfaces. Elevation effects were also measured for stereoscopic surfaces to provide comparison data and to confirm the findings of Schumer and Ganz.

Corrugated depth surfaces, specified in the usual way by motion parallax information, were used as adapting stimuli. The spatial frequency of the adapting corrugation was fixed at 0.2 cyc/deg and thresholds were measured for test corrugations of 0.1, 0.2 and 0.4

cyc/deg. After an initial adapting period of 30secs, observers were presented with cycles of a 20secs adapting period followed by a test period of 10secs. During the test period, corrugations were randomly presented at each of the test frequencies and thresholds were measured by an ascending method of limits. Throughout the adapting period the phase of the parallax depth surface was reversed every two seconds to prevent any build-up of a negative depth aftereffect. This procedure ensured that no phase-specific aftereffect could build up, and was considered to be more effective than the vertical scanning procedure used by Schumer and Ganz. Each adaptation trial consisted of 24 cycles of adapt and test, so that eight threshold measurements were made for each of the test spatial frequencies. During the test period, the amplitude of the test corrugation was gradually increased until the observer could identify the number of cycles present in the test surface and this point was taken as an estimate of the threshold. The thresholds measured on these adaptation trials were compared with those measured on pre-and post-control trials. These trials consisted of fifteen 30sec. cycles comprising a 20 secs. presentation of a flat parallax depth surface followed by a 10 sec. test period, during which the threshold for one of the test surfaces was again estimated by an ascending method of limits. As a measure of threshold elevation, the mean threshold value measured for each test spatial frequency during the adaptation trial was subtracted from the sum of the mean thresholds measured in the pre and post trials.

It was found that, on average, no threshold elevation occurred after inspection of a parallax depth surface, for any of the three observers. The variability in threshold data was found to be rather high for all observers. It was concluded that the procedure used was not adequate to measure the small elevation effects that might be predicted in this situation. It was, therefore, decided to measure threshold elevation effects for stereoscopic surfaces to see whether more reliable data could be obtained.

In this experiment, the adapting stimuli were corrugated disparity surfaces with a spatial frequency of either 0.2 or 0.4 cyc/deg. During adaptation, the phase of the adapting corrugation was again reversed every two seconds to destroy any negative depth aftereffect. Thresholds were measured, as before, by an ascending method of limits in the brief period following presentation of the adapting surface. The test corrugation was, randomly, one of six spatial frequencies which spanned the adapting spatial frequency. Threshold elevation was calculated by subtracting the threshold values obtained in the adaptation trials, from those obtained in control trials where a flat zero disparity surface was presented during the adapting period. The data are plotted in Figure 5.7, for two observers. The results obtained again showed a high variability, although there does seem to be a slightly increased threshold for test corrugations at the same spatial frequency as the adapting surface.

In conclusion, the methods used to measure threshold elevation in the present experiment were not adequate to determine whether such elevation occurred for either parallax or stereoscopic surfaces. It is possible that the use of a counterphase adapting corrugation increased the variability of the measurements by introducing temporal as well as spatial modulation of the stimulus. A more detailed investigation using forced choice procedures and counterphase depth gratings of varying temporal frequencies would have to be carried out before any

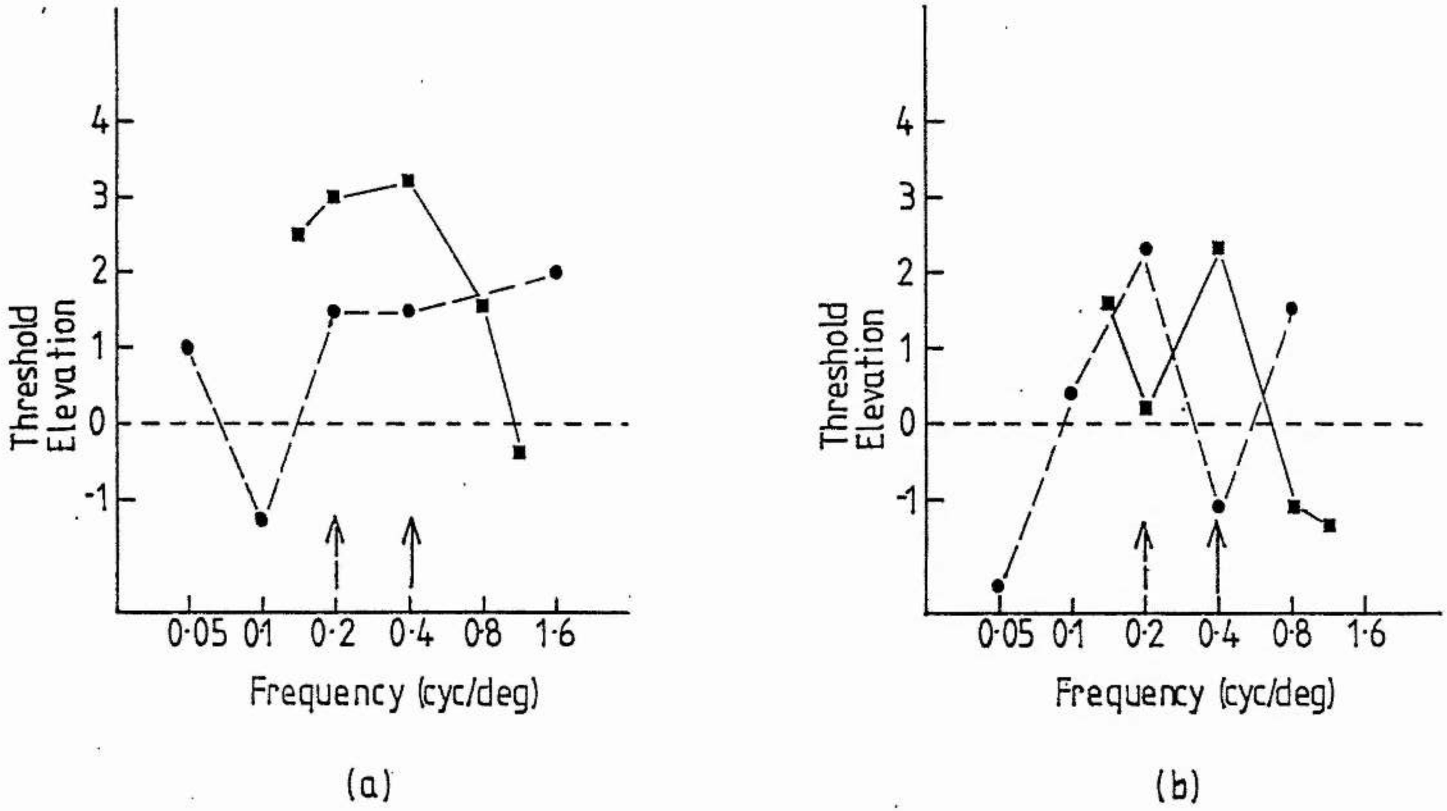


Figure 5.7.

The amount of threshold elevation measured after adapting to a corrugated stereoscopic surface of either 0.2 (dotted lines) or 0.4 (filled lines) cycles/degree, for test surfaces of different spatial frequencies. During adaptation the phase of the adapting corrugation alternated to prevent the build-up of a phase-specific negative aftereffect. Data are shown for two observers MEG (a) and AL (b). Threshold elevation is expressed in arbitrary units where a value of 7 corresponds to a doubling of peak to trough depth at threshold following adaptation.

conclusions about the existence of underlying depth processing mechanisms could be drawn from the study of this type of adaptation effect.

iii) Hypercyclopean depth aftereffects

The third type of adaptation effect predicted by an independent channel model of processing is that following adaptation the perceived characteristics of stimuli similar to the adapting stimulus will be altered. For example, after prolonged inspection of a luminance grating at a particular spatial frequency, the perceived spatial frequency of test gratings of slightly higher (lower) spatial frequencies, is shifted so that they appear to have a higher (lower) frequency than in the unadapted state. An analogous effect in the depth domain was reported by Tyler (1975b). He reported that, after viewing a depth surface which consisted of a high frequency disparity grating above a low frequency disparity grating (Figure 5.8), then, in a test surface which contained two disparity gratings of the same spatial frequency, the lower grating appeared to have a higher depth spatial frequency than the lower. Although a demonstration stereogram is provided in the published paper, Tyler does not provide empirical data to support the reported effect as no attempt was made to measure the strength of this depth spatial frequency shift.

Tyler does, however, report a tilt aftereffect for disparity gratings for which data were collected. After adapting to disparity gratings of a high spatial frequency, which were oriented at a range of angles from the horizontal, observers were asked to adjust the orientation of a test grating of the same frequency so that it appeared

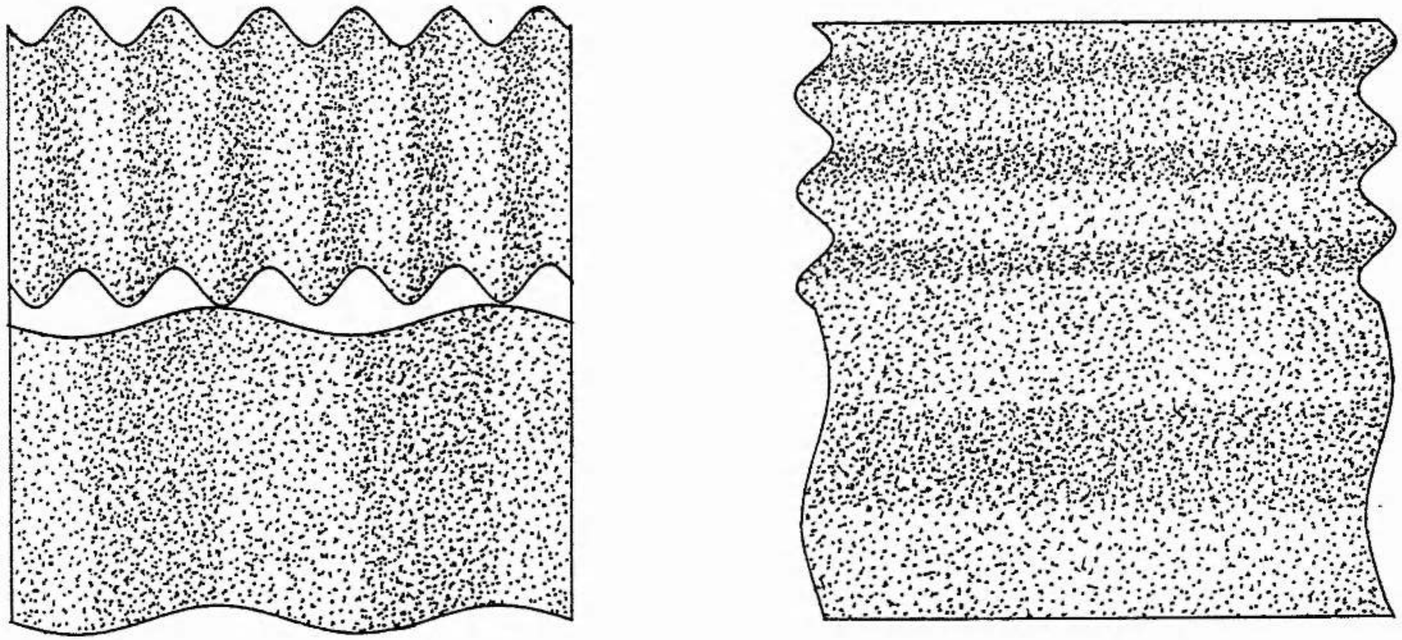


Figure 5.8.

Adapting surfaces used to measure the depth spatial frequency shift. Observers adapted to either a horizontally or vertically oriented depth surface where the upper half contained a depth corrugation with a spatial frequency of three times the spatial frequency of the lower corrugation. The test surface contained depth corrugations of the intermediate frequency in both lower and upper halves.

to be horizontal. The largest tilt aftereffect, of about two degrees, was found for adapting gratings oriented 20–30 degs from the horizontal. This is analogous to the tilt aftereffect found for luminance gratings where the maximum effect occurs when the adapt and test gratings differ in orientation by about 10–15 degs (Campbell and Maffei, 1971). Tyler calls these two types of stereoscopic aftereffect, hypercyclopean, in contrast to the cyclopean aftereffect, or negative stereoscopic aftereffect, obtained with random dot stereograms and steady fixation. This term highlights the fact that his effects are due to adaptation to the actual form of the stereoscopic surface rather than to the particular depth values over a certain area. This suggests that they occur at a high level within the disparity processing system, where the overall form of the depth surface is extracted. Tyler's observations suggest that at this level the mechanisms involved are selectively tuned to the size and orientation of stereoscopic form.

An attempt was made to measure the depth spatial frequency shift observed by Tyler for stereoscopic depth gratings, and to look for a similar effect for depth gratings specified by motion parallax information. Observers viewed an adapting surface, illustrated in Figure 5.8, which consisted of a high spatial frequency depth grating above a lower frequency grating, such that the two frequencies always differed by a factor of three. The corrugations were either oriented vertically, or horizontally, as shown. During an adapting period of a couple of minutes, the observer scanned the surface in a direction orthogonal to the depth contours, to prevent the build-up of negative depth aftereffects. After the adaptation period, a test surface was presented which contained two depth gratings with the same spatial frequency, and this frequency had a value halfway between the values of the low and high frequencies in the adapting surface. Despite using a wide range of adapting frequencies no measurable difference in frequency was observed between the two halves of the test surface. This was true both when the depth surfaces were specified stereoscopically and when they were specified by motion parallax. A small effect in the predicted direction was noted for the highest adapting frequencies used (0.5 and 1.5 cyc/deg), but this was not large or reliable enough to measure with a nulling technique. This finding suggests that any observed depth spatial frequency shift is small and, hence, throws some doubt on Tyler's suggestion of independent mechanisms tuned to the spatial frequency of depth modulation.

In summary, although large negative phase-dependent aftereffects were found after prolonged viewing of corrugated depth surfaces when the depth was specified by either motion parallax or stereopsis, it was difficult to find a clear example of a phase-independent adaptation effect using the present methods and stimuli. Studies by Schumer and Ganz (1979) and Tyler (1975b) suggest that such effects can occur, at least for stereoscopic surfaces, and that they provide evidence for phase-independent mechanisms responsive to different frequencies and orientations of disparity modulation over space. These findings were not, however, replicated in the present study. It was suggested above that the observed negative aftereffects, which are phase-specific, are best explained as arising from the adaptation of mechanisms which respond to changes in depth over space. The sensitivity functions reported in chapter 4 suggest that subsets of these mechanisms might be responsive to depth modulation over different spatial areas. The present evidence suggests that, if these mechanisms exist, then they are phase-dependent, that is, they depend on certain characteristic types of depth change over fixed retinal areas and are not organised into phase-independent channels. Further evidence for the existence of such mechanisms has been provided by looking at simultaneous depth contrast effects which are a direct result of spatial interactions in the depth domain.

Chapter 6 Simultaneous Contrast Effects for Parallax and Stereoscopic Depth

6.1 Introduction.

Within many sensory dimensions it has been found that the perceptual characteristics of a neutral test area are affected by the properties of the surrounding area. For example, a neutral grey disc on a red surround appears to be green, that is, it takes on the colour complementary to its surround. This is an example of simultaneous colour contrast (Kirschmann, 1890; Purkinje, 1825). A similar contrast effect in the movement domain is demonstrated by the phenomenon of induced movement, first reported by Duncker (1929), where a stationary test spot appears to move when it is surrounded by a moving frame. An analogous induced tilt effect occurs for line stimuli (Gibson, 1933) and, for luminance gratings, the perceived orientation and spatial frequency of a patch of grating are affected by the orientation and spatial frequency of surrounding or adjacent gratings (Mackay, 1973, Klein, Stromeyer and Ganz, 1974). These perceptual contrast effects illustrate that the perceptual characteristics of adjacent spatial areas are not independent and hence, that perceptual processing in general involves interactions between stimulus information from neighbouring areas. Simultaneous contrast effects have therefore been used as evidence for the existence and extent of spatial interactions within various processing mechanisms (Ratliff, 1965; von Bekesy,1968; Anstis, 1975).

Within the depth domain, the existence of simultaneous contrast effects analogous to those found for other sensory dimensions, can be demonstrated by showing that the depth of a particular area is affected by the depth values of surrounding regions. This chapter describes several effects of this kind which have been found for depth surfaces, where the depth within the surface was specified either by motion parallax or by stereoscopic information. Such effects illustrate that spatial interaction is an important aspect of processing within both the parallax and stereoscopic systems.

6.2 Preliminary observations.

Simultaneous contrast effects in the depth domain can readily be observed in many depth surfaces with different three-dimensional structures. Stereoscopic simultaneous contrast effects were described by Anstis (1975), who used a random dot stereogram to portray the depth surface illustrated in Figure 6.1. It consists of two discs which are at the same disparity and which would, therefore, normally appear to lie in the same depth plane. However, the lower disc is surrounded by a surface at an uncrossed disparity with respect to the discs and appears to lie behind them, while the upper disc is surrounded by an area at a crossed disparity which appears to be nearer. On viewing this surface, the lower disc appears to lie nearer to the observer than the upper due to the depth contrast between the discs and their surrounds. This effect is not an aftereffect but occurs immediately upon viewing the depth surface.

The first demonstration of simultaneous contrast in the parallax depth domain was similar to the display described by Anstis. The parallax surface was produced in the usual way, using a distortion

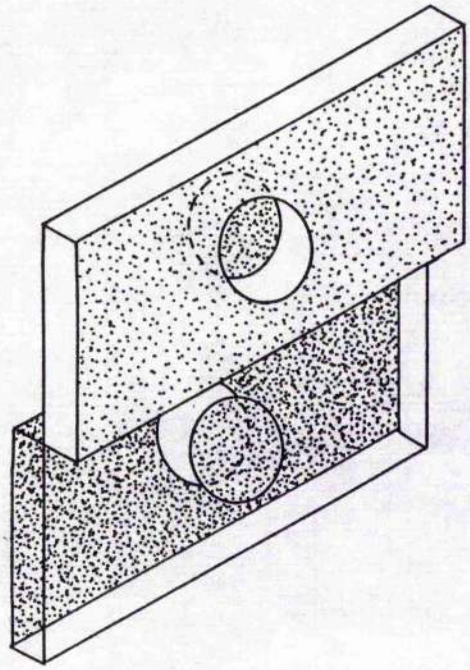


Figure 6.1.

The depth surface used by Anstis (1975) to demonstrate the presence of simultaneous contrast effects in the depth domain. The surface was portrayed using a random dot stereogram and contained two discs which were at the same disparity. The discs appeared, however, to lie at different distances from the observer when the upper disc was surrounded by a surface nearer the observer and the lower disc by a surface farther away. The upper disc appeared to lie farther away than the lower disc.

signal which was amplitude modulated according to the position of the observer's head. This signal introduced patterns of relative motion into a random dot pattern which the observer viewed while moving laterally on a chinrest. In this particular case, the parallax information simulated that produced by the surface illustrated in Figure 6.2a. To do this, the shape of the parallax signal was made the same as the shape of the profile of the intended depth surface. The surface itself consisted of two horizontal bars between which there was no relative motion,-thus specifying that they were at the same depth. The upper bar was surrounded by an area whose relative motion specified a surface behind the bar, and the lower bar was surrounded by an area whose relative motion specified a nearer surface. When observers viewed this parallax stimulus, they perceived a solid three-dimensional surface which contained two bars surrounded by areas of different depths. It was found, however, that the two bars appeared to lie at different distances from the observer, with the upper bar appearing nearer than the lower bar. Hence, parallax depth surfaces show a similar type of contrast effect to that demonstrated by Anstis for stereoscopic surfaces. To confirm this similarity using identical surfaces in the two domains, the surface in 6.2a was also displayed stereoscopically, where the depth in the surface was specified by binocular disparities rather than relative motion. As for the parallax surface of the same shape, the upper bar appeared to lie nearer to the observer than the lower bar.

Several other depth contrast effects can be observed with simple depth surfaces. For example, when viewing a surface which contains two flat, frontoparallel depth planes, situated at different distances and separated by a sharp step in depth, most observers report that the two

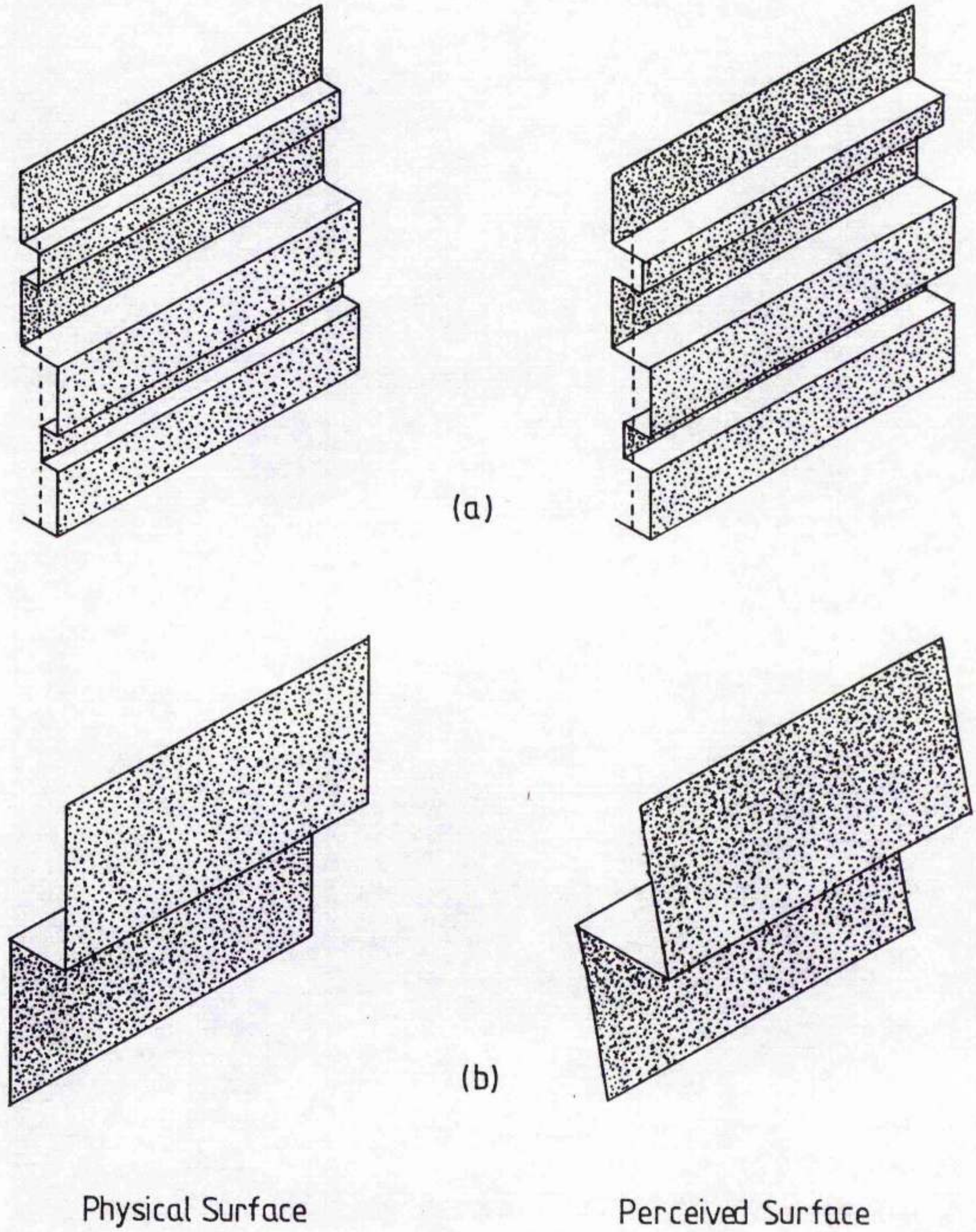
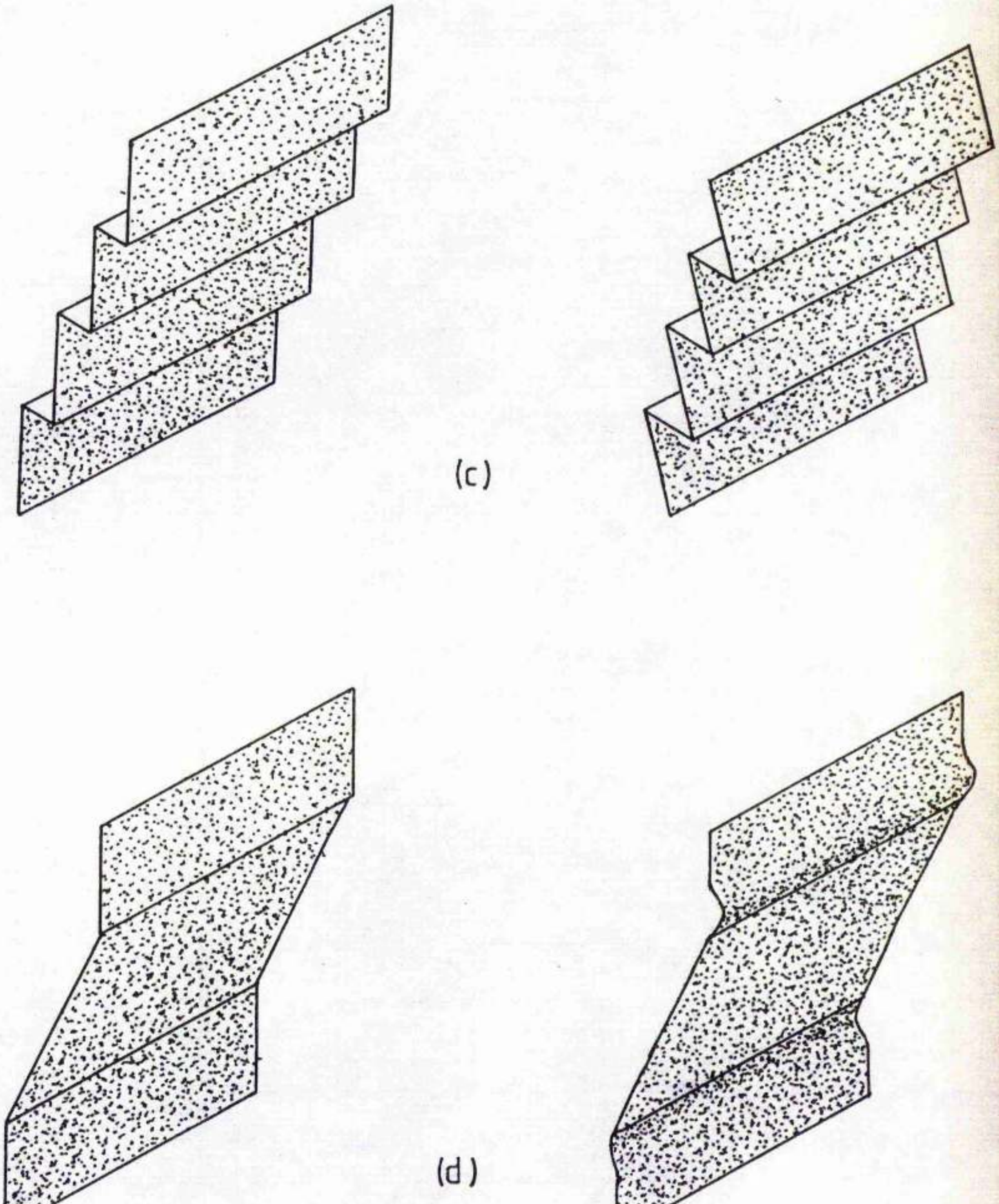


Figure 6.2.

Four examples of simultaneous depth contrast :
In (a) the upper bar appeared to lie in front of the lower bar although they were physically at the same depth, due to the depth contrast from the surrounds. In (b) where there is a simple step change in depth between the upper and lower halves of the surface (which both lie in the frontoparallel plane), the two halves appeared to be sloping away in depth. Similarly for a surface with a staircase depth profile (c) the individual steps appear to slope in depth. A type of "Mach band" can also be observed for depth (d); a smooth ramp in depth appears to have narrow troughs or bumps at its edges.



(c)

(d)

Physical Surface

Perceived Surface

depth planes appear to slope away in depth rather than appearing to lie in the frontoparallel plane (Figure 6.2b). This effect appears to be analogous to the apparent luminance ramps observed on viewing a staircase luminance profile (Ratliff, 1965). A closer analogy can be observed for a surface with a staircase profile in depth where the individual steps of the profile appear to slope in depth (Figure 6.2c). In the luminance domain, a powerful illusion which has been attributed to lateral inhibitory interactions between luminance detectors, is the presence of Mach bands (Mach, 1959; Ratliff, 1965). These illusory bands of light and dark are perceived at the boundaries of smoothly changing luminance gradients. Again, an analogous effect occurs for depth, a smooth ramp in depth appears to have narrow depth bumps at its edges (Figure 6.2d). These depth effects could be observed both when the depth surfaces illustrated in Figure 6.2 were specified by parallax motion and when the depth was specified by binocular disparities.

The observations just described show that simultaneous contrast effects do occur in the depth domain, for parallax as well as stereoscopic depth. However, they do not give any idea of the strength of the effects or the assumed underlying spatial interactions. The aim of the following experiment was to measure the strength of the contrast effect observed for the surface shown in Figure 6.3a. This surface produced a powerful simultaneous contrast effect which could be measured easily using a nulling technique. It consisted of a depth plane which sloped gradually from the top to the bottom of the surface, and halfway down the surface was a horizontal bar which was vertical, lying in the frontoparallel plane, at a distance equivalent to the centre distance of the surrounding sloping plane. Immediately on viewing this depth surface, the centre bar, which was physically

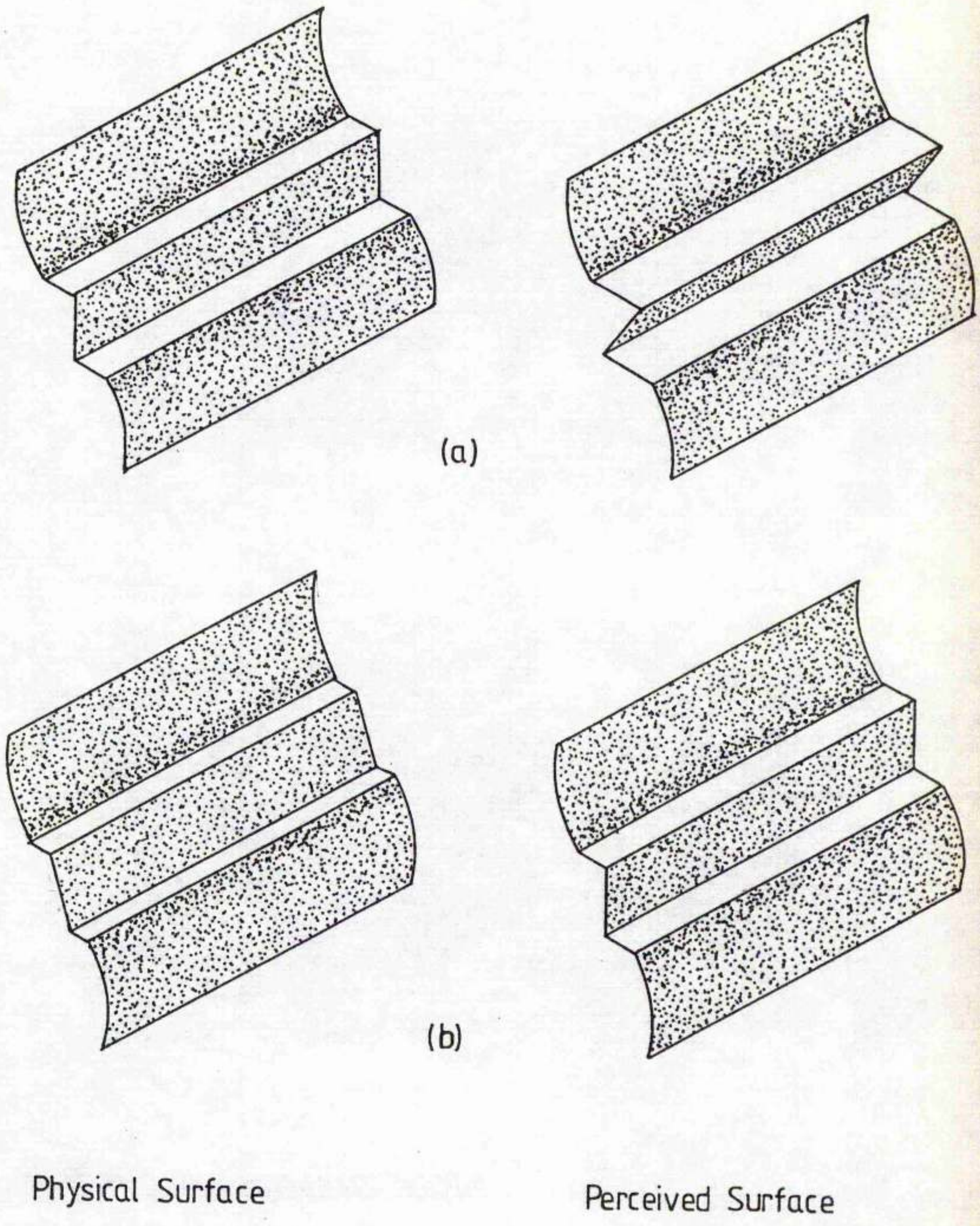
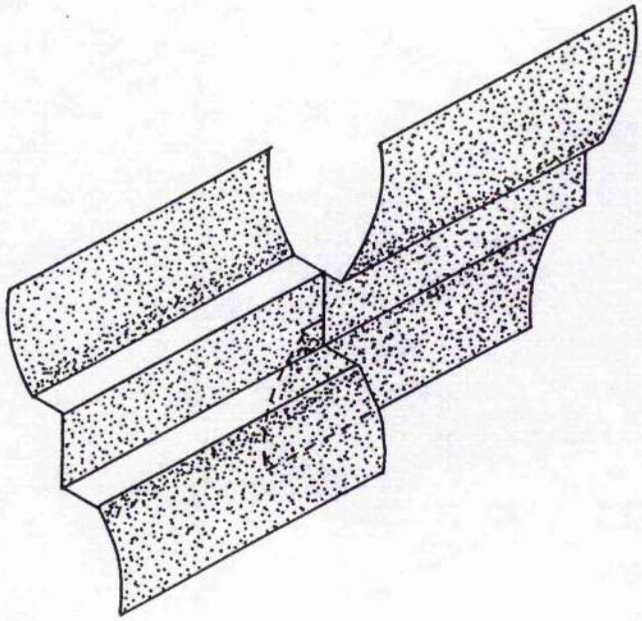


Figure 6.3.

The surface used for the simultaneous contrast experiment consisted of a surface sloping in depth from the top to the bottom of the display. Cut out of this surface was a centre bar which was vertical in the frontoparallel plane. Immediately upon viewing this surface the centre bar appeared to be sloping in depth in the opposite direction to the surround (a). This contrast effect was measured by a nulling technique. A physical depth slope was added to the centre bar until it appeared vertical (b). The actual surface used in the experiment consisted of two halves in which the inducing surface sloped in opposite directions (c). The contrast effect acted in opposite directions in the two halves of the centre bar so that it appeared twisted along its length.



(c)

vertical, appeared to slope in depth and the direction of the depth slope was opposite to the direction of the slope of the surrounding inducing surface. The degree of slope induced into the centre horizontal bar could be used as an indication of the strength of the effect. This was measured using a nulling technique to cancel the induced slope of the centre of the centre bar. This technique was easy to use and produced reliable results. It also indicated that a depth slope induced by contrast can be, in some sense, added with physical depth, although the precise nature of this interaction is unclear.

6.3 Methods and procedure.

The strength of the simultaneous contrast effect was measured for both parallax and stereoscopic surfaces whose shape is shown in Figure 6.3a. For the parallax display, the distortion signal was a waveform of the same shape as the desired depth profile, and this signal was amplitude modulated according to the position of the observer's head, to produce the appropriate pattern of relative movement as the observer moved from side to side. For the stereo display, a signal of the same shape was used to provide binocular disparities between the two patterns in the stereoscopic viewing apparatus. In both cases, the waveform was produced either by multiplying a sine and pulse waveform of appropriate frequencies (Figure 6.4) or by using the Wavetek 175 arbitrary waveform generator, which was programmed to produce a digital waveform of the appropriate shape. As shown in Figure 6.4, the waveform could be altered to vary the slope of the surrounding depth plane in the simulated surface, and, independently, to vary the slope of the centre horizontal bar.

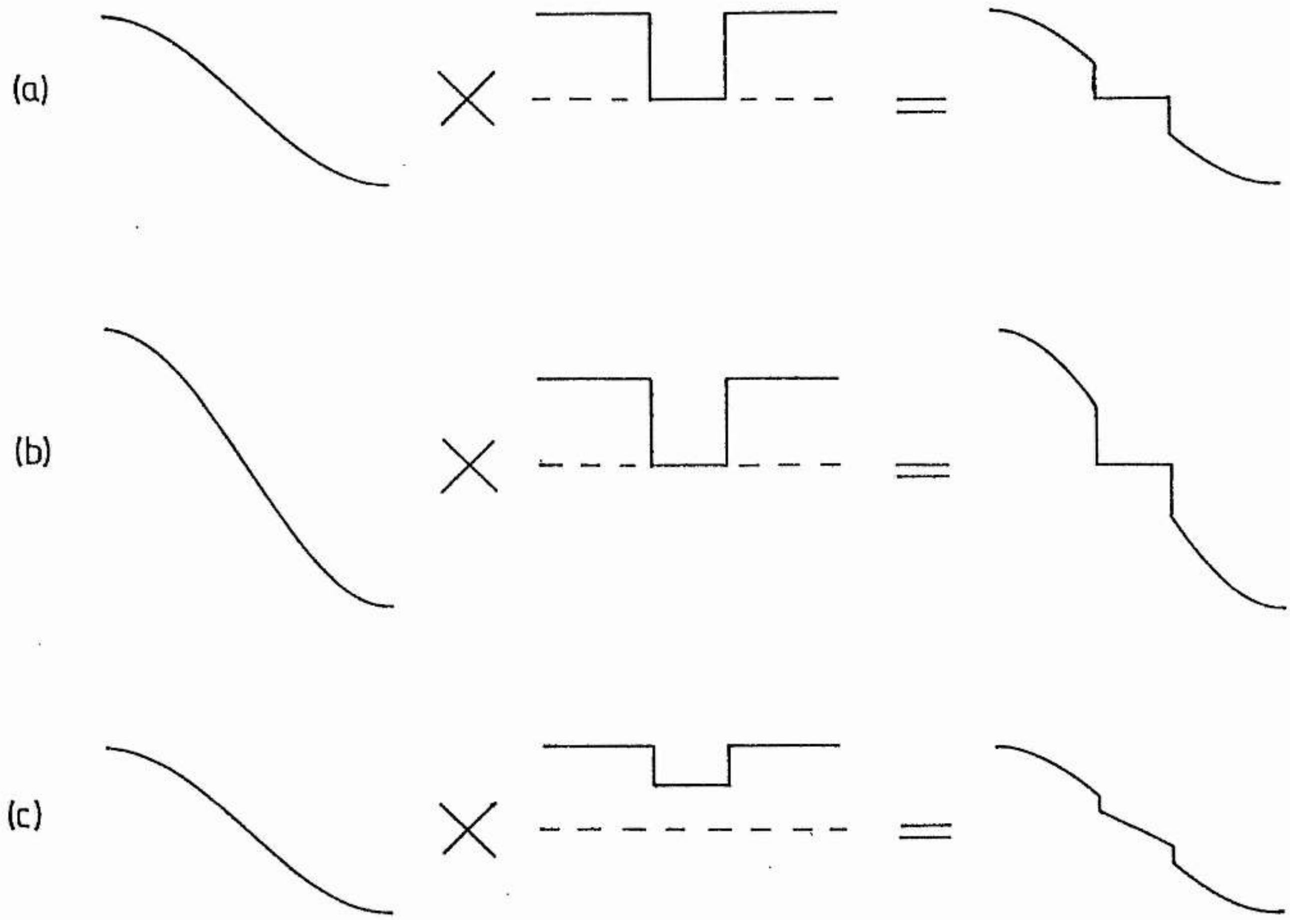


Figure 6.4.

To produce the surface shown in Figure 6.3. the parallax, or disparity signal consisted of a sine waveform multiplied by a pulse waveform of an appropriate frequency (a). Increasing the amplitude of the sine component increased the slope of the inducing surface without changing the slope of the centre bar (b). Decreasing the amplitude of the pulse component (which was offset from zero) altered the slopeof the centre without affecting the surround (c). This allowed the contrast effect to be measured by introducing a physical slope to the centre bar.

Initially, when the centre bar was physically set to be vertical (in the frontoparallel plane) it appeared to slope in the opposite direction to the slope of the surrounding surface (Figure 6.3a). To measure the strength of the contrast effect, the observer adjusted a potentiometer which varied the slope of the centre bar, without altering the shape or slope of the inducing surround. The observer's task was to vary this slope until a null position was found where the centre bar appeared to be vertical and to lie in the frontoparallel plane (Figure 6.3b). The degree of slope that had to be added in to the centre bar, to cancel the contrast effect and make the bar appear vertical, was then taken as a measure of the strength of the effect. The strength of the effect was measured for surfaces where the inducing surrounds had different degrees of slope.

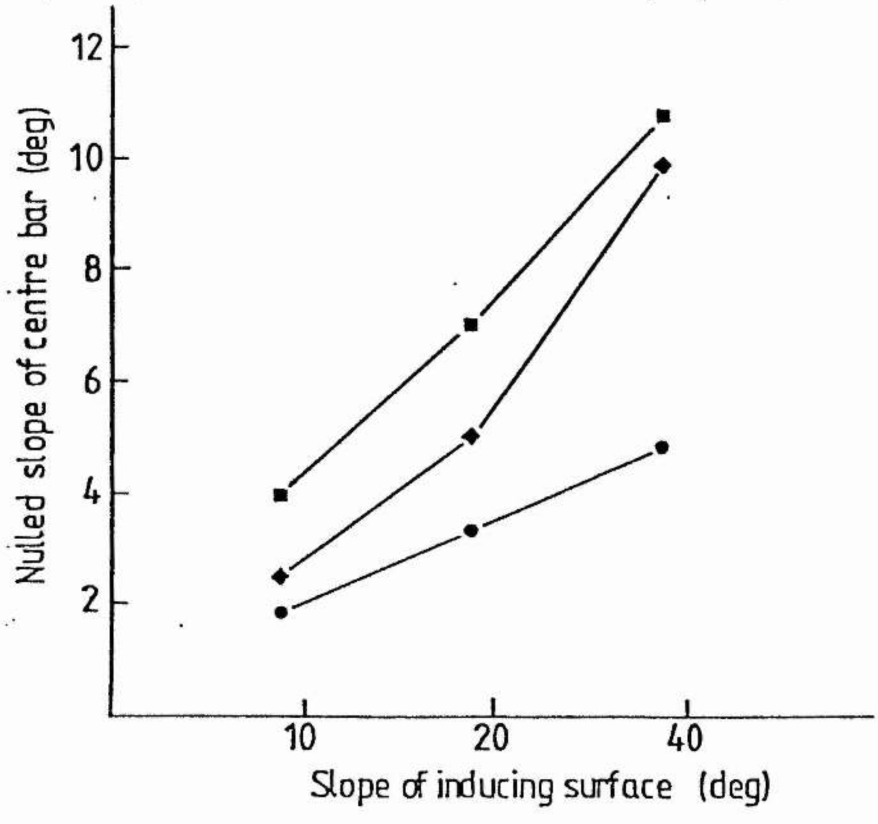
In practice, it was found that observers varied considerably in their settings of the apparent vertical. Even in the absence of a surrounding inducing slope, the centre bar was set to an apparent vertical which differed by several degrees from the true vertical. For most observers the subjective vertical was tilted away from the true vertical but there were large differences between individuals. In order to overcome this source of variation, the depth surface actually used to measure the contrast effect consisted of two halves. In the left hand half, the horizontal centre bar was surrounded by a surface which, from the top to the bottom of the surface, sloped from far to near and so appeared to be tilted away from the observer. In contrast, the centre bar in the right hand half, was surrounded by a surface sloping from near to far and appeared to tilt towards the observer (Figure 6.3c). The two halves of the surround now sloped in opposite directions, and so when the centre bar was physically vertical the induced slope acted in opposite directions for the two halves. The centre bar then appeared to be twisted in depth along its length. The observer's task, for this modified stimulus, was to adjust a potentiometer which altered the slope of the centre bar by the same amount, but in opposite directions, for the two halves of the bar. The observer had to adjust this control until the centre bar no longer appeared to be twisted in depth and the two halves appeared to be aligned.

The contrast depth surface illustrated in Figure 6.3c was specified by either parallax or stereoscopic information. The contrast effects were measured on different days for the parallax and stereo depth surfaces. In each session, a randomised sequence of trials comprising five presentationsof three different surfaces,was presented to each observer. The three surfaces were identical except that the slope of the surrounding inducing surface varied, being either 9, 18 or 33 degrees from the vertical. On each trial the slope of the centre bar was intially set to be vertical and the observer was asked to judge whether the two halves of the centre bar appeared to be misaligned and whether the bar appeared to be twisted in depth. If a contrast effect was observed, the observer was asked to adjust the potentiometer until the bar no longer appeared twisted and the two halves were aligned. Observers were given a maximum of 20 secs to make a setting and were asked to scan the whole surface during this time to avoid the build up of a depth aftereffect. The amount of slope that had to be added in to cancel the contrast effect was recorded and the mean setting for each of the three surfaces was taken as a measure of the strength of the effect. The contrast effect was measured for seven observers for both parallax and stereoscopic depth surfaces. In each case, five observers were naive to the purpose of the experiment.

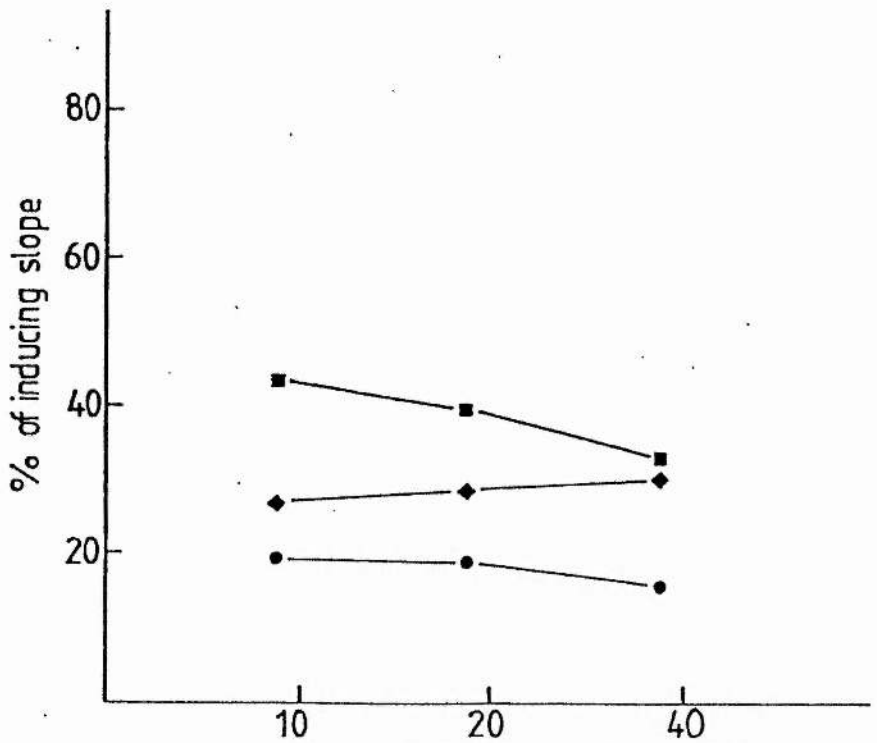
6.4 Results.

Initially the depth surface was presented with the two halves of the centre bar set to be physically vertical. All seven observers reported a substantial contrast effect on viewing the depth surface. The centre bar appeared to be twisted along its length so that each half appeared to slope in the opposite direction to its surrounding surface. This was true both when the depth surface was specified by relative motion and when it was specified by binocular disparities. Observers found the nulling task straightforward and were able to cancel the contrast effect by adjusting the slopes of the two halves of the centre bar until they appeared to be aligned. The mean amount of slope that had to be introduced to cancel the contrast effect was expressed both in absolute terms, as the degree of induced slope, and in percentage terms, as a percentage of the slope of the inducing surface. A 0% effect, therefore, would have occurred when, at the null position, the two halves were set to be truly vertical and a 100% effect would have occurred when they were set at the same slope as the surrounding surface. The data obtained for parallax and stereoscopic surfaces are plotted in absolute terms in Figures 6.5a and 6.6a respectively, and in percentage terms in Figures 6.5b and 6.6b. The data shown are mean data for the seven observers (diamonds) and individual data for two experienced observers.

Large simultaneous contrast effects of around 30% to 40% were found for both parallax and stereoscopic surfaces. As the slope of the



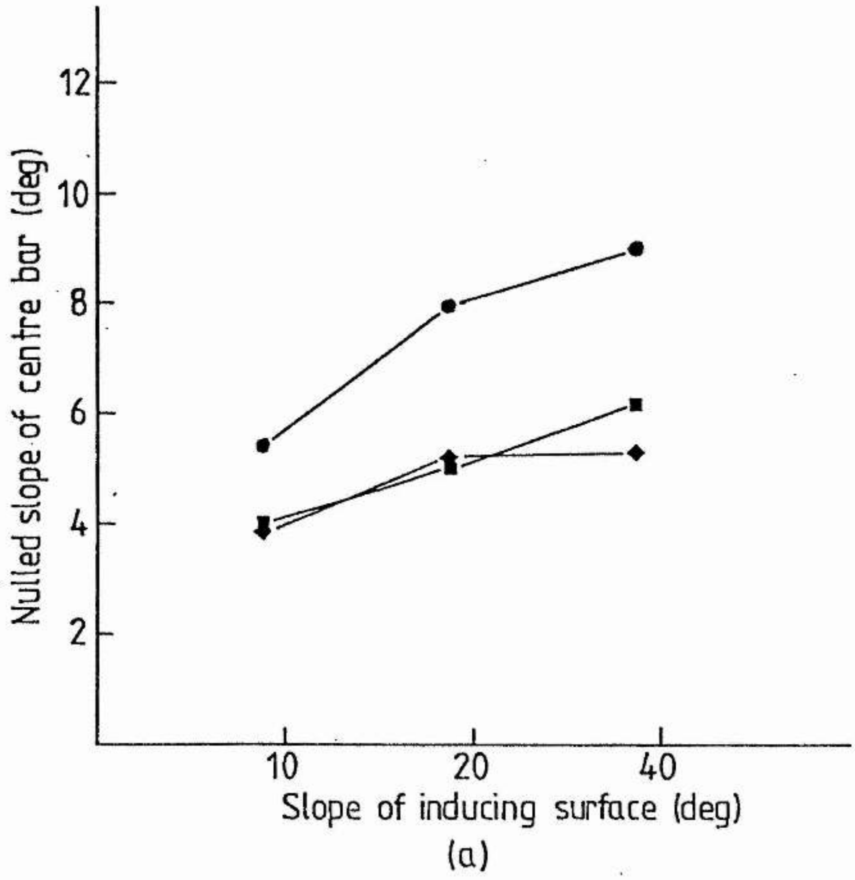
(a)



(b)

Figure 6.5.

Simultaneous contrast effects for motion parallax depth: The amount of physical slope that had to be introduced into the centre bar to make the two halves appear aligned, is shown as a function of the slope of the inducing surface (a). The same data are replotted in (b) as a percentage of the slope of the adapting surface. Mean data for seven observers (diamonds) and individual data for two experienced observers MEG (circles) and BJR (squares) are plotted.



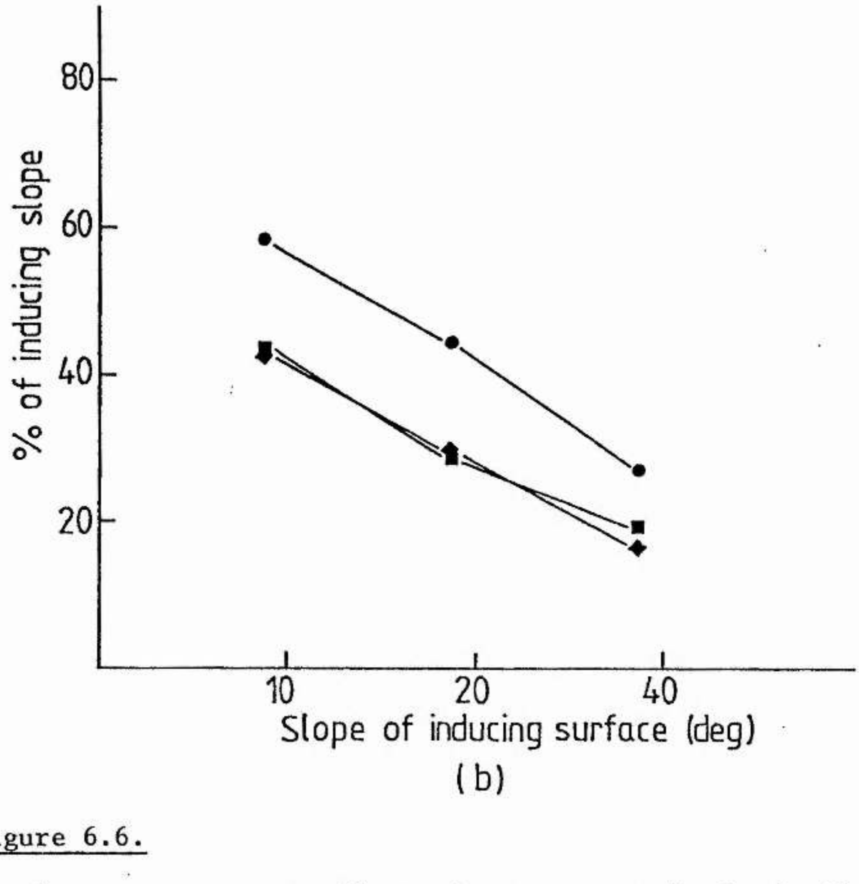


Figure 6.6.

Simultaneous contrast effects for stereoscopic depth: The amount of slope that had to be introduced into the centre bar to cancel the contrast effect is shown as a function of the slope of the inducing surface (a). The same data are replotted in (b) as the percentage of the slope of the inducing surface that was necessary to cancel the contrast effect. Mean data are shown for seven observers (diamonds) and individual data for MEG (circles) and BJR (squares).

inducing surface increased, the absolute size of the contrast effect also increased. This increase was roughly linear for parallax surfaces so that the percentage effect remained roughly constant. For stereoscopic surfaces the percentage effect decreased with increasing inducing slope.

6.5 Discussion.

The large simultaneous contrast effects found in this experiment demonstrate that spatial interactions are an important aspect of processing for both the motion parallax and stereoscopic depth systems (Graham and Rogers, 1982a). This suggests that the spatial organisation of the underlying processing mechanisms might be an essential feature in extracting information about depth structure.

i) Velocity contrast effects

For depth surfaces specified by motion parallax it seems likely that the presence of depth contrast effects is related to some velocity contrast effects which have been reported previously in the literature. In 1973, for example, Loomis and Nakayama reported that two spots which were physically moving with the same velocity, appeared to move at very different velocities when one spot was surrounded by dots moving at a faster rate and the other was surrounded by slower moving dots (Figure 6.7a). The spot surrounded by slower moving dots appeared to move faster than the spot surrounded by faster moving dots. Loomis and Nakayama suggested that this velocity contrast effect was due to velocity processing mechanisms which respond to relative movement between neighbouring areas and have centre-surround antagonistic

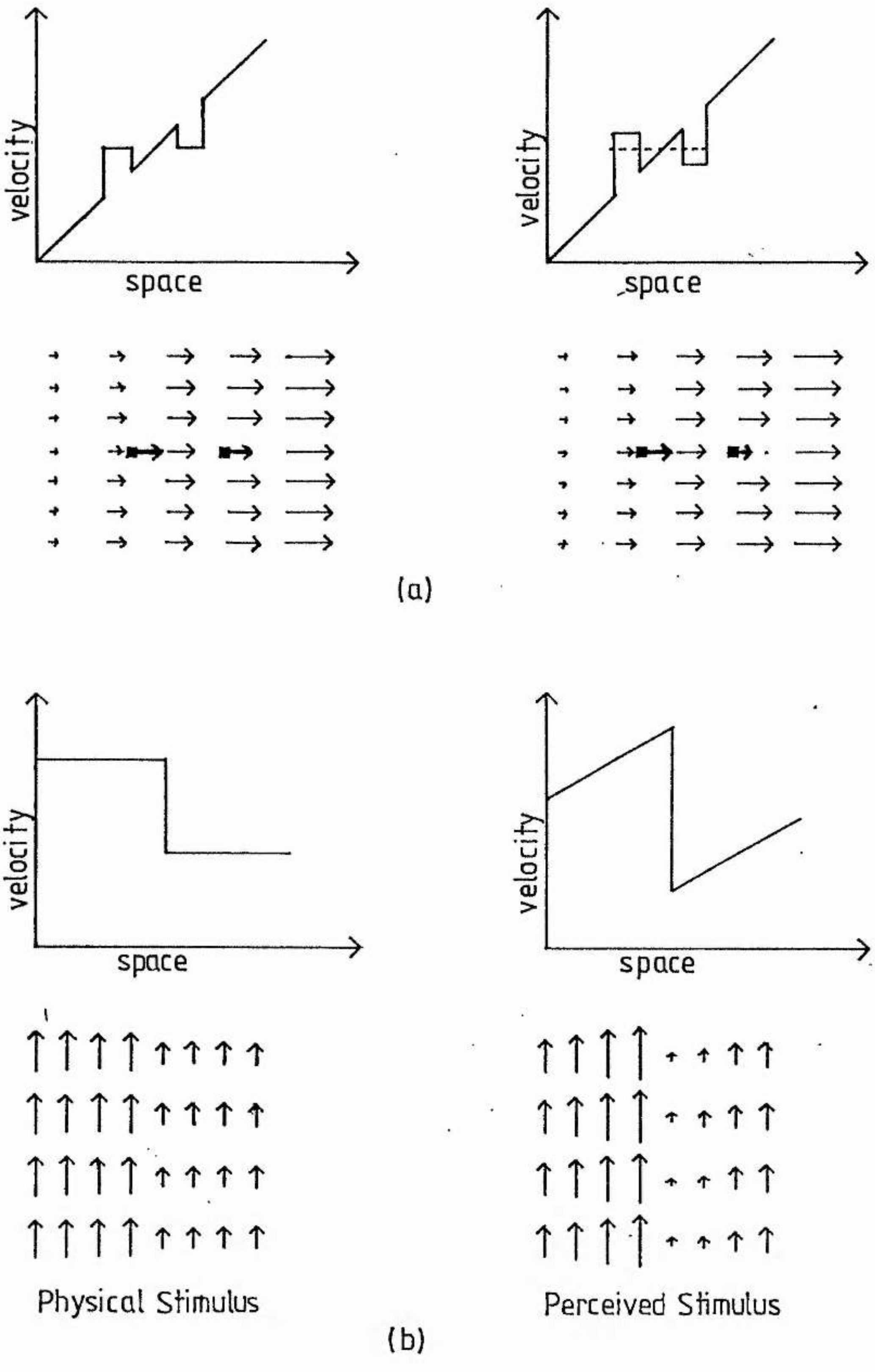


Figure 6.7.

Velocity contrast effects: (a) Loomis and Nakayama (1973) found that two spots which were moving with the same velocity appeared to be moving at different velocities when one spot was surrounded by slower moving dots and the other by faster moving dots. (b) A related effect was noticed by Walker and Powell (1974). When two halves of a moving random dot pattern moved at different velocities there appeared to be a gradient of velocities within each of the two halves which served to emphasise the change in velocity at the border separating the two halves.

properties similar to those found physiologically (Barlow and Levick, 1965; Sterling and Wickelgren, 1969; Bridgeman, 1972; Burns, Gassanov and Webb, 1972; Frost, 1978; Frost et al., 1981; Allman et al., 1982).

A related finding was reported by Walker and Powell (1974), who investigated the perceived velocities of different rows of a grid of moving dots. When the top rows of the pattern were moving at twice the velocity of the bottom rows, there appeared to be a gradient of velocity within the upper and lower halves which led to the velocity difference at the border being overestimated (Figure 6.7b). Walker and Powell explain this effect as due to spatial inhibitory interactions between velocity sensitive channels which act to enhance discontinuities in velocity.

These two velocity contrast effects are analogous to two of the depth contrast effects described previously and illustrated in Figure 6.2a and 6.2b. It is therefore possible that the motion parallax contrast effects arise from the operation of the same mechanisms that give rise the velocity contrast effects. This possibilty is supported by an observation reported in the paper by Loomis and Nakayama (1973). They observed that, as the density of the dots in their display increased, the display began to be perceived as a surface sloping away in depth. When this occured all the dots appeared to lie on the perceived surface and hence to move at the same velocity. The two target spots also appeared to move at the same velocity and so the velocity contrast effect was no longer observed. Unfortunately, they do not report whether a depth contrast effect replaced the velocity effect so that one target spot appeared to be nearer the observer than the other. The findings of the present study suggest that depth contrast effects would be present in this situation.

A convincing demonstration of the relation between velocity and depth simultaneous contrast effects has been given by Holmgren (1974). He looked at the velocity contrast effects which occurred for a wide range of velocity distributions. The stimuli were random dot patterns the rows of which moved in the same direction at different speeds. Observers perceived a pattern of dots continuously moving behind a window and they were asked to report the perceived velocity of different rows of the pattern. Simultaneous contrast effects for velocity were found which were analogous to the staircase and Mach band effects which occur for luminance and depth (Figure 6.2c). The perceived velocity of any row was dependent on the velocity of neighbouring rows and, in general, the perceived velocity differences at velocity edges or discontinuities were exaggerated. Holmgren also noted that these velocity patterns often gave rise to the perception of strong depth effects and these were accompanied by depth contrast effects. Where, previously, illusory bumps had occurred in the perceived velocity profile, ditches and ridges were now perceived in the depth profile. That is, near a velocity border or discontinuity, contrast effects either resulted in perceived irregularities of velocity within the area to either side of the border, or in perceived bulges and indentations within a three-dimensional depth surface. In summary, it seems very likely that the velocity and depth contrast effects arise from the operation of the same mechanisms. Which effect is perceived depends on whether the velocity distributions are perceived as patterns of relative motion or are interpreted as three-dimensional surfaces. Although not explicitly mentioned by Holmgren, it would be expected, from the present findings on parallax surfaces, that the perception of a three-dimensional surface would predominate for high density patterns, with monocular viewing, under conditions where the overall translation component of the surface could be easily registered.

The most detailed study of simultaneous velocity contrast was carried out by Tynan and Sekuler (1975). They looked at the perceived velocity induced in a circular region of random dots, when movement was introduced into the random dot surround. They found that, when the centre dots remained stationary they were perceived to move slowly in the opposite direction. The velocity of this induced movement soon reached an asymptotic value as the surround velocity increased. When the centre dots moved at a constant velocity in the opposite direction to the surround, the perceived velocity increased slightly as the surround velocity increased. When they moved in the same direction, the perceived velocity first decreased then increased as the surround speed reached and then exceeded that of the centre. These results again suggest that inhibitory interactions occur between velocity sensitive units in adjacent areas of visual space. In addition, this particular study indicates that these inhibitory interactions show velocity tuning, with maximum inhibition occurring when centre and surround move with the same velocity. As the difference in velocity between centre and surround increases there is a release from inhibition which leads to a relative enhancement of the velocity difference.

Tynan and Sekuler also looked at the depth separation which was perceived between the centre and surround in their displays. When the centre was stationary the amount of depth separation increased with the speed of the surround, but when the centre moved in a direction opposite to the surround it was independent of surround speed. When both centre and surround moved in the same direction, the perceived depth separation increased as the difference in speed increased. These depth percepts accompanied the velocity effects just described, and were not an alternative percept as in the Holmgren study. The important result is that the perceived depth separation did not increase with the increasing velocity difference when centre and surround moved in opposite directions. Such an increase would be expected from traditional formulations of motion parallax. It is possible that this result is due to a limit to the perceived depth separation that can be perceived by a single velocity difference. Once this maximum has been attained the depth separation remains constant as the velocity difference is increased further. Support for this argument comes from observations of motion parallax depth surfaces where, as the amplitude of the relative motion signal is increased to a large value, the perceived depth reaches a maximum. Above this value relative motion starts to be perceived within the random dot surface. An alternate explanation is that the postulated inhibitory spatial interactions in the velocity domain only occur between mechanisms with the same directional tuning. In this case, however, different explanations would have to be advanced for the velocity and depth contrast effects.

Other studies by Anstis and Reinhardt-Rutland (1976) and Nakayama and Tyler (1978) also suggest inhibitory spatial connections in the velocity domain. Nakayama and Tyler looked at the motion induced in stationary lines by harmonic motion of flanking lines. They found that the extent of induced motion depended on both the amplitude and velocity of surround motion. They interpret their results in terms of hypothetical velocity sensitive mechanisms having a centre-surround organisation with respect to velocity and a range of receptive field sizes, where the preferred velocity increases for increasing field size. In their later study on sensitivity to sinusoidal velocity distributions (which was discussed in chapter four), Nakayama and Tyler (1981a) further suggest that these mechanisms show a double opponency such that motion opposite to the preferred direction inhibits the response in the centre of the receptive field and releases the inhibition in the surround.

In summary, studies of simultaneous velocity contrast strongly suggest the existence of spatial interactions in the velocity domain which can best be characterised in terms of velocity detecting mechanisms which have a receptive field structure with an excitatory centre and inhibitory surround and a preferred velocity which may be related to the receptive field size.

The simultaneous depth contrast effects obtained in the present study for depth surfaces specified by motion parallax information seem to share similar characteristics to the previously reported velocity contrast effects. It seems possible, therefore, that the parallax depth contrast effects arise from the receptive field organisation of the velocity-sensitive mechanisms which are involved in processing depth from relative motion. Velocity mechanisms with the hypothesised type of receptive field would, in fact, be simple types of relative motion, or shear detectors, and such mechanisms have been shown, on theoretical grounds, to provide a good basis for a motion parallax processing system (Longuet-Higgins and Prazdny, 1980; Koenderink and van Doorn, 1976; Clocksin, 1980b). Moreover, as indicated in the last chapter, an explanation of the strong negative aftereffects obtained for parallax depth can best be explained in terms of such mechanisms. This argument would imply that depth contrast effects arise from the spatial interactions between velocity mechanisms rather than at the level of depth processing itself. From the results so far it is not possible to decide whether spatial interactions also occur at the higher level where the relative motion is disambiguated and depth information extracted. If spatial interactions only occur within velocity mechanisms it would seem unlikely that depth information from motion parallax and stereopsis could directly interact in any quantitative way. Experiments designed to look at interactions between stereopsis and parallax are reported in chapter eight.

ii) Stereoscopic Depth Contrast

The present experiment found that large simultaneous contrast effects also occurred for depth surfaces specified by binocular disparities. It was suggested in the last chapter that the negative aftereffects obtained for stereoscopic depth can best be explained in terms of mechanisms which process relative disparity, or changes in disparity over space. The demonstration of simultaneous contrast for stereoscopic depth indicates that spatial interactions, probably of an inhibitory kind, occur for the disparity processing of neighbouring areas. It is likely, therefore, that mechanisms responding to relative disparity also show the type of centre-surround receptive field organisation that has been suggested for parallax mechanisms. Such a conclusion is in agreement with the findings of Schumer and Ganz (1979) who postulated the existence of centre surround mechanisms of different receptive field sizes to explain the summation and threshold elevation effects which they obtained for stereoscopic surfaces.

The similarity in the receptive field characteristics of the underlying depth processing mechanisms in the motion parallax and stereoscopic systems, would account for the observed similarity in the perceived depth contrast effects. The relationship between the degree of inducing slope and the size of the contrast effects was, however, found to be slightly different for motion parallax and stereopsis. This may be due to slight differences in the spatial extents of the depth receptive fields in the two cases, but more probably reflects differences in task requirements.

One important simultaneous contrast effect which has been studied in the luminance domain is the Craik-O'Brien-Cornsweet illusion. Investigations of an analogous effect in the depth domain have yielded some interesting data which shed some more light on the nature of the mechnisms underlying depth processing and in particular on the likely receptive field organisation of such mechanisms. These experiments are described in the following chapter.

Chapter 7 Anisotropy in the Processing of Depth Information

7.1 The Craik-O'Brien-Cornsweet illusion for depth.

i) Preliminary observations

In the last chapter, the existence of strong simultaneous contrast effects was used to argue for the presence of spatial interactions in both the parallax and stereo processing systems. These contrast effects show that the perceived depth of an area can be greatly affected by the depth values of adjacent areas. The spatial arrangement of relative motions or disparities is therefore crucial in determining perceived depth. This chapter initially describes an experiment which looked at another example of the influence of spatial interactions in depth processing.

In the previous chapter depth contrast effects were described which appear to be analogous to contrast effects which occur within other stimulus dimensions such as luminance or velocity. One of the most interesting contrast effects in the luminance domain is the Craik-O'Brien-Cornsweet illusion, named after the researchers who independently reported the effect (Craik, 1966; O'Brien, 1958; Cornsweet, 1970). The illusion occurs when viewing a pattern with the luminance profile shown in Figure 7.1. The profile consists of two areas of equal luminance separated by a spur-shaped change in luminance. On viewing such a pattern, the two equi-luminous areas appear to be of very different brightnesses (Figure 7.1). This illusory brightness difference has been attributed to the relative

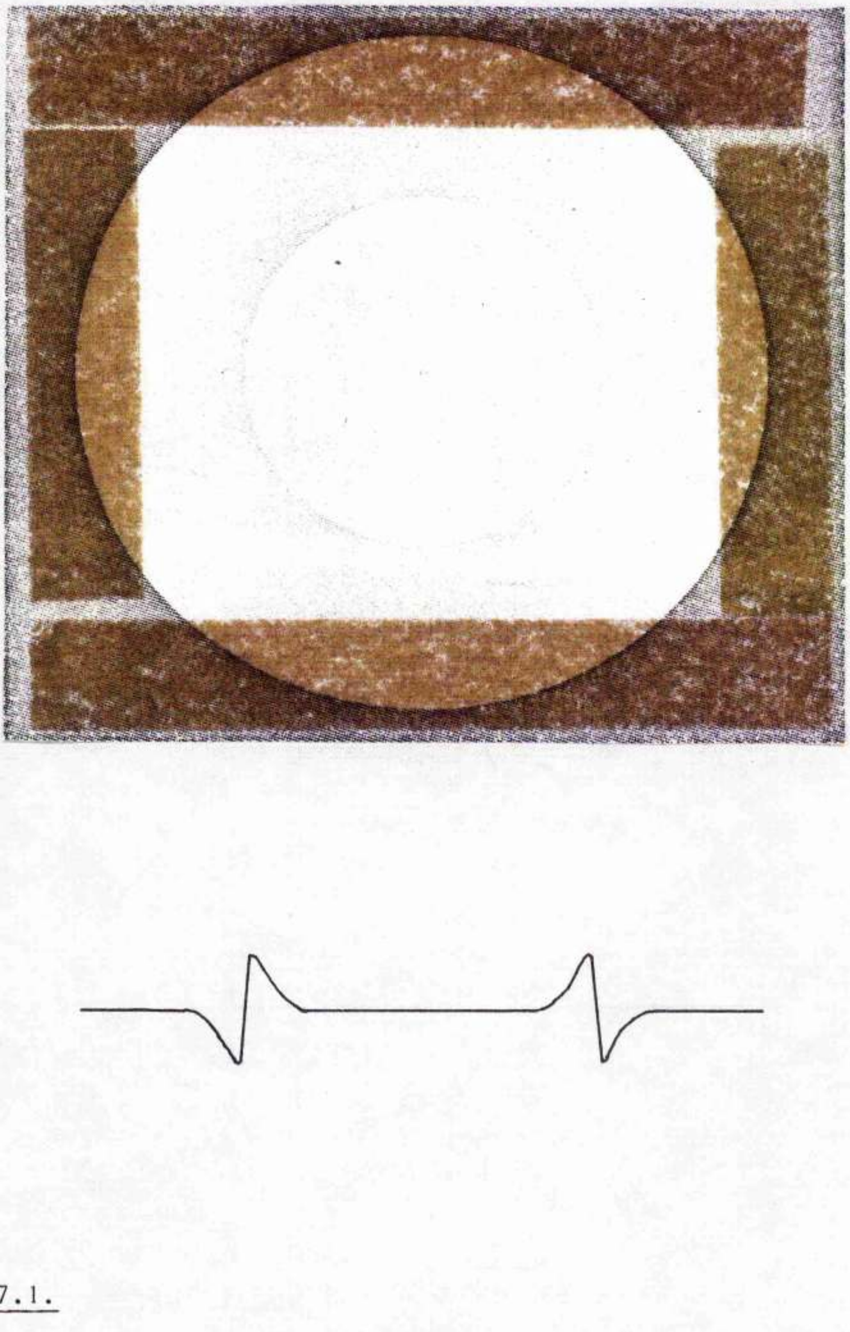


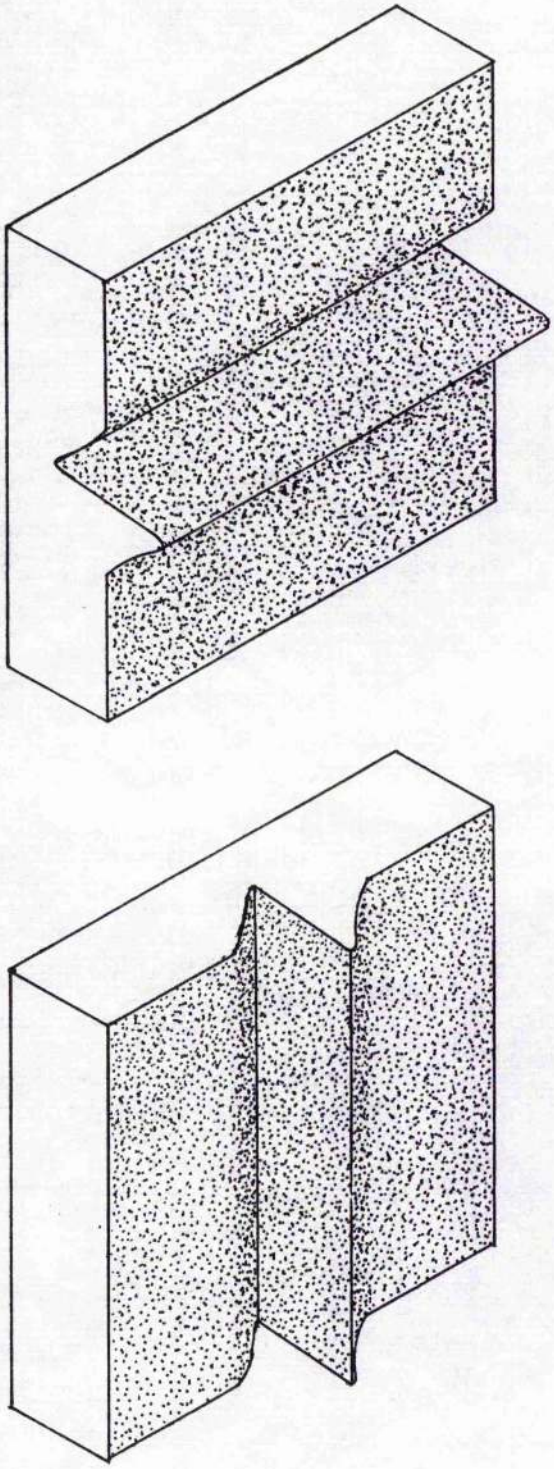
Figure 7.1.

The Craik-O'Brien-Cornsweet illusion for luminance:
Due to the variation in luminance at the contour, the centre of the pattern appears to be brighter than the surround, although physically they are both at the same luminance. The luminance profile of the pattern is shown underneath.

insensitivity of the visual system to the slowly changing luminance gradients in the pattern compared to the sharp change at the centre of the pattern. The visual system's response to the sharp change therefore outweighs that due to the slower change and a step change in brightness is signalled (Anstis, 1975; Ratliff, 1972). It is generally thought that the insensitivity to low frequency change reflects the operation of lateral inhibitory interactions between luminance processing mechanisms (Ratliff, 1965; Cornsweet, 1970). This insensitivity is also reflected in the higher detection thresholds which are observed for contrast modulated gratings of low spatial frequencies (Campbell and Robson, 1968).

An analogous Craik-O'Brien-Cornsweet illusion in the depth domain was reported in 1978 by Anstis, Howard and Rogers for stereoscopic depth surfaces. They produced stereoscopic depth surfaces which had a depth profile similar to the luminance profile that produces the illusion in luminance. This depth surface is illustrated in Figure 7.2b. It consisted of two areas at the same depth which were separated by a spur-shaped change in depth where the surface curved away from the observer, then came sharply forward and finally curved more slowly back to the depth of the flank. Anstis, Howard and Rogers found that the two areas at either side of the profile, which were equidistant from the observer, appeared to lie at different depths with the right hand flank appearing to be nearer than the left. This illusory depth difference was, therefore, directly analogous to the illusory brightness difference perceived on viewing the Cornsweet luminance profile.

After finding large simultaneous depth contrast effects for both



(a)

(b)

<u>Figure 7.2.</u>

Cornsweet depth surfaces with a depth profile similar in shape to the luminance profile shown in Figure 7.1. The depth surfaces consist of two areas at the same depth which are separated by a spur-shaped change in depth. Cornsweet surfaces could be produced with the central Cornsweet edge oriented either horizontally (a) or vertically (b).

stereoscopic and parallax surfaces, it was decided to investigate the Cornsweet depth illusion as an additional example of spatial interactions in the depth domain. A parallax depth surface with a Cornsweet profile was produced in the usual way. A waveform of the same shape as the desired depth profile was amplitude modulated according to the position of the observer who moved from side to side while viewing the surface. In preliminary observations it was found that a parallax depth surface with a Cornsweet shaped profile was perceived **veridically**. That is, the expected illusory depth difference between the flanks of the profile was not observed. This unexpected result was also obtained in a subsequent attempt to replicate the earlier study of Anstis, Howard and Rogers using stereoscopic depth surfaces specified by binocular disparities. Again, when a stereoscopic surface with a Cornsweet profile was observed, the two flanking areas which were physically at the same depth were perceived, veridically, to lie at the same distance from the observer. No illusory depth effect was observed, a finding which failed to confirm the observations by Anstis, Howard and Rogers.

While investigating the reasons for this failure to replicate the earlier study, it was found that the orientation of the depth surface appeared to be an important parameter. When the surface was oriented so that the sharp edge was horizontal (Figure 7.2a) there was little or no depth illusion, but an illusory depth difference between the equidistant flanking areas was observed when the Cornsweet edge was oriented vertically (Figure 7.2b). In the preliminary observations, which had been made for parallax surfaces, the Cornsweet depth surface had been presented with the sharp contour of the profile lying horizontal while, in the earlier study by Anstis, Howard and Rogers, the depth surface had been presented with the contour oriented vertically. This seemed to be the crucial difference which determined whether an illusory depth difference was perceived between the equidistant flanks of the surface. To further explore this interesting anisotropy, a detailed study of the Cornsweet depth illusion was carried out for both parallax and stereoscopic depth surfaces. In each case, the extent of the illusion was measured for Cornsweet-shaped depth surfaces which were either oriented with the contour horizontal or with the contour vertical.

In addition, the extent of the Cornsweet illusion was measured as a function of the width of the area of the changing part of the depth surface. Since, in the luminance domain, the illusion is attributed to a relative insensitivity to slow changes in luminance, the rate of change in depth of the various parts of the profile was thought to be likely to influence the extent of the illusion in the depth domain. Varying the area of the central part of the profile changed the rate of change in depth and hence the predominant depth spatial frequencies present in the surface.

ii) Methods and Procedure

The motion parallax and stereoscopic display characteristics were the same as those used in previous experiments. A signal of the same shape as the desired Cornsweet profile was produced using the Wavetek 175 arbitrary waveform generator which was pre-programmed by the computer. This signal was amplitude modulated to provide the relative motion signal for the parallax display, or was used to introduce binocular disparities in the stereoscopic display. The

Cornsweet profile can be considered to be the sum of two ogive functions containing different rates of change (Figure 7.3a). One ogive specifies a slowly changing step in one direction while the other specifies a faster changing step in the opposite direction. When the amplitude of the two components is equal a profile of the traditional Cornsweet shape is produced. If the amplitudes are not equal there is an offset between the two flanks of the profile (Figure 7.3b and c). A Cornsweet depth illusion is observed when the two equidistant flanking areas of the depth surface are perceived to lie at different depths. The illusion, therefore, shows the same effect as reducing the amplitude of the slowly-changing ogive, which introduces an offset between the two flanking areas. This fact was exploited to allow the extent of the Cornsweet illusion to be measured.

A nulling task was used to measure the extent of the illusion. The observer's task was to cancel the illusory depth difference perceived between the flanks of the depth surface so that they appeared to lie at the same depth. To do this the observer effectively adjusted the amplitude of the faster changing ogive component of the depth profile. This had the effect of adjusting the relative depth of the two flanks. If, as in the luminance domain, the depth illusion is due to the relative insensitivity of the system to the slower changing component of the profile compared with the faster changing profile, then the illusion has the same effect as a reduction in the amplitude of the slow component. The task of cancelling the illusory depth difference is then equivalent to making the effective amplitude of the two components equal, that is, of reducing the amplitude of the faster changing component until it matches the effective amplitude of the slower. The strength of the illusory effect could therefore be

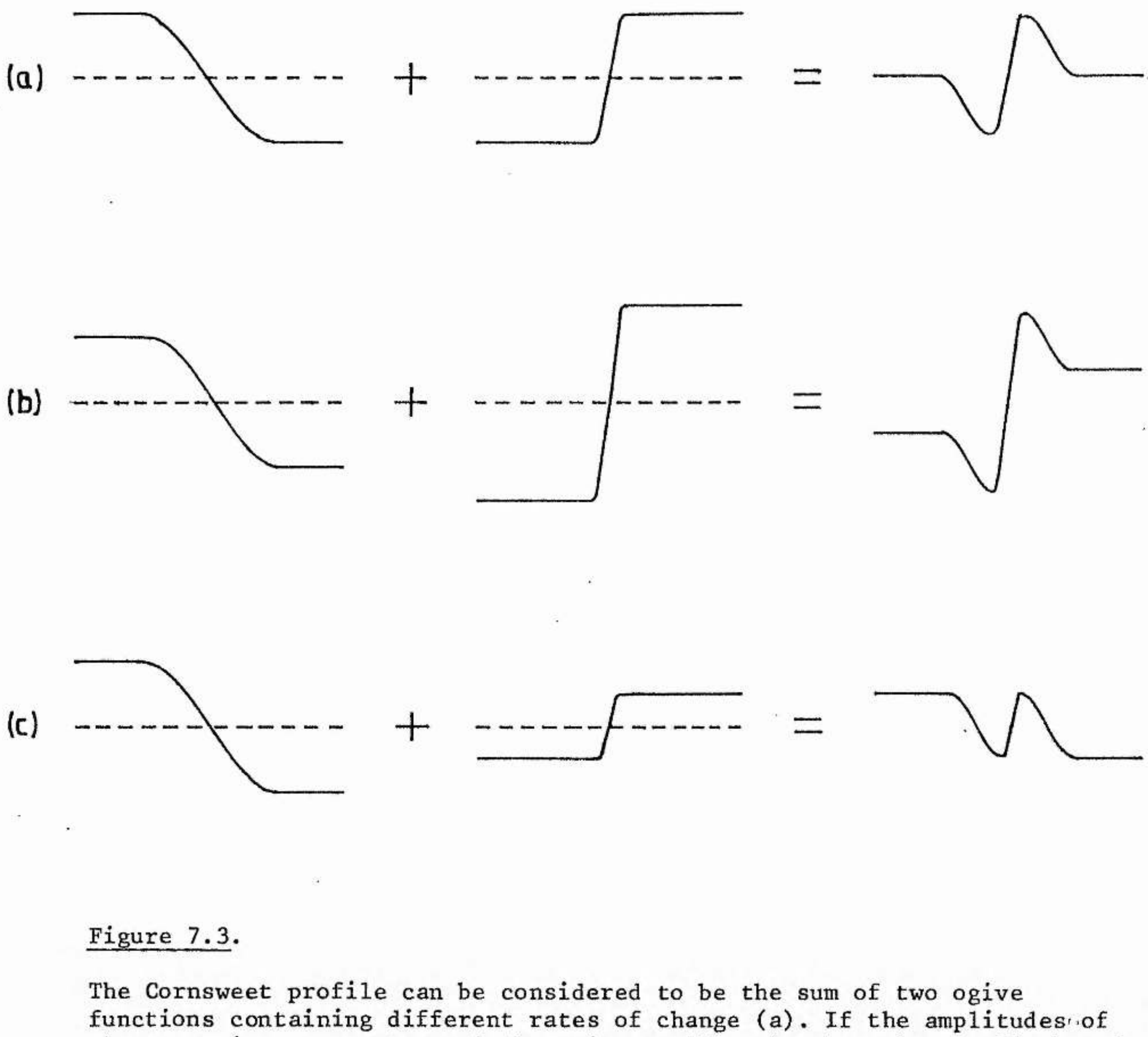


Figure 7.3.

The Cornsweet profile can be considered to be the sum of two ogive functions containing different rates of change (a). If the amplitudes of the two ogives are not equal there is an offset between the two flanks of the compound profile (b and c). In the Cornsweet illusion, when the two flanks are equidistant, they appear to be offset in depth in the direction shown in (b). The illusory effect can therefore be measured by reducing the amplitude of the faster changing ogive component (as in (c)), which introduces a physical offset between the flanks, until the illusory offset has been cancelled and the two flanks appear to be equidistant.

expressed as the percentage reduction in the amplitude of the faster changing component that was needed to compensate for the visual system's insensitivity to the slower component. In these terms, a zero percent effect was one in which, at the null setting, the two flanks were set to be physically equidistant. A hundred per cent effect, on the other hand, was one where the amplitude of the faster changing component was set at zero and the two flanks were physically at different depths, as specified by the slower changing component. (The nulling procedure had the effect of adjusting the size of the depth discontinuity at the centre of the profile while leaving the slowly changing part unchanged (see Figure 7.3)).

To investigate the effect of varying the spatial gradients within the Cornsweet profile, the extent of the illusion was measured for the four depth surfaces illustrated in Figure 7.4. In these surfaces, the number of cycles of the Cornsweet profile present in the depth surface was increased so that the area covered by a single cycle of the profile was reduced. Besides the one cycle surface which contained one Cornsweet edge in the middle of the surface and which had gently sloping sides which extended over ten degrees of visual angle, surfaces containing 2, 4 and 8 Cornsweet edges which contained slopes of increasing sharpness (extending over 5, 2.5 and 1.25 degrees respectively), were also used as stimuli. In all cases the depth amplitude at the sharp edge of the surface was equivalent to 8 min arc of disparity. Another variable that was manipulated in the experiment, was the amplitude of the Cornsweet signal which was reversed for half the trials. For the simultaneous contrast effect described earlier in the chapter, it had been found that the null judgements were affected by large observer biases in the setting of the apparent vertical. The

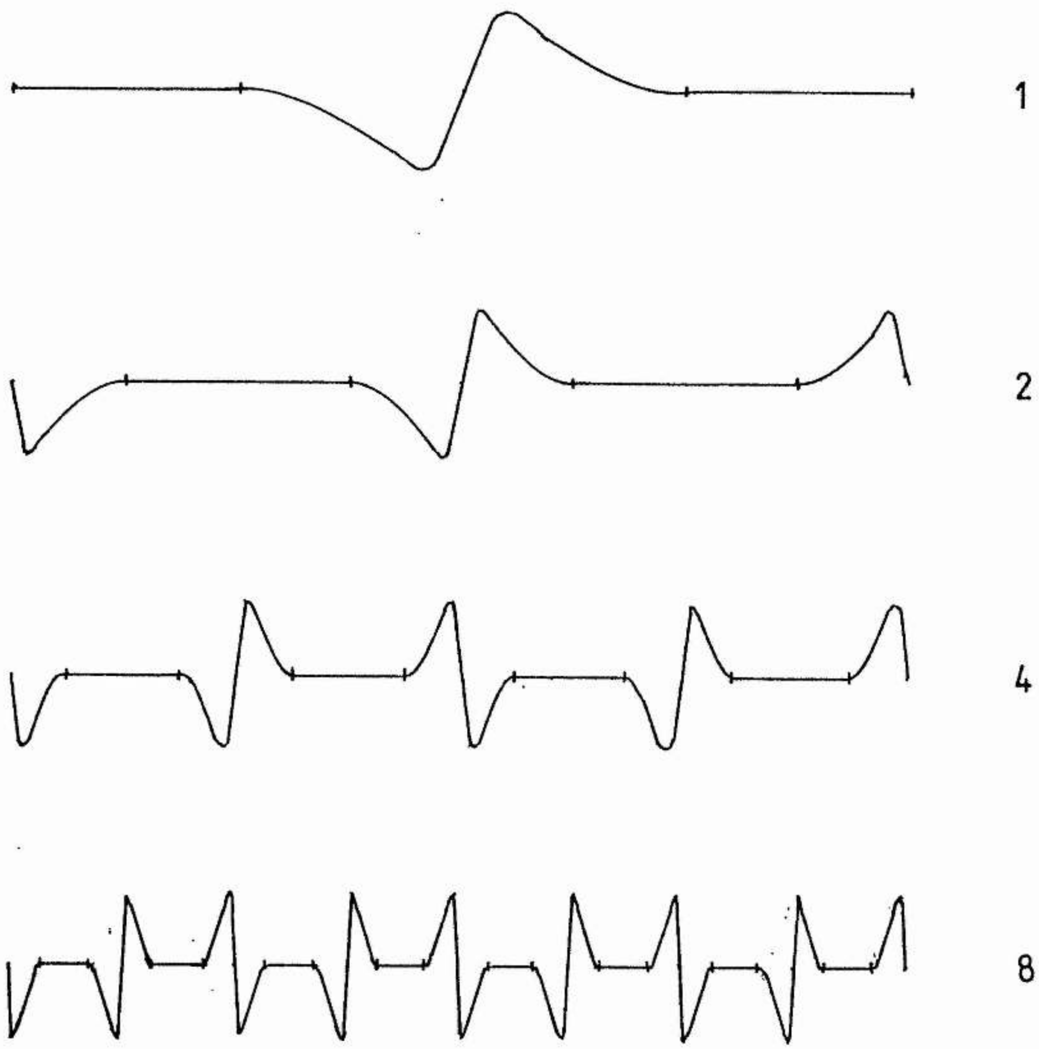


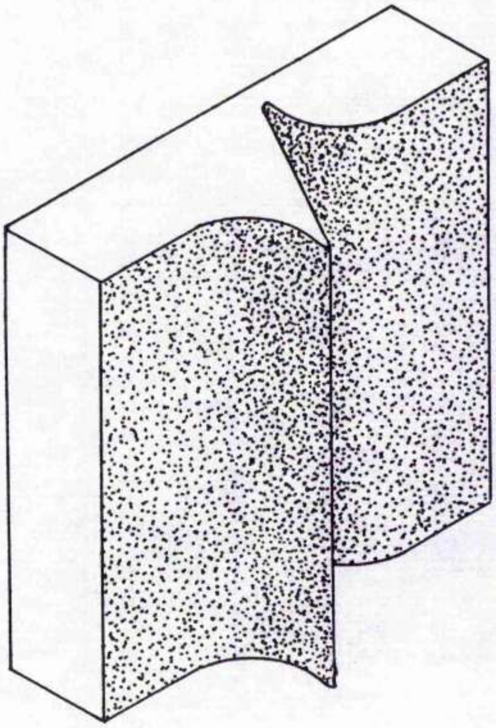
Figure 7.4.

To investigate the effect of varying the spatial gradients within the Cornsweet surface, the extent of the illusion was measured for four depth surfaces with the four depth profiles shown here. The depth surface contained either one, two, four or eight repetitions of the basic Cornsweet profile, as shown.

present experiment required the two flanking areas to be adjusted to lie in the frontoparallel plane and so was likely to be subject to similar observer biases. To overcome this problem, the extent of the illusion was measured when the Cornsweet signal was of both normal and inverted phase. This manipulation had the effect of reversing the depth relationships within the Cornsweet surface, so that areas which had previously sloped toward the observer then sloped away, and vice versa (see Figure 7.5). Averaging the extent of the illusion for the two amplitude conditions compensated for the effects of individual biases in judging the frontoparallel plane.

The Cornsweet depth surface was presented with the edge oriented either horizontally or vertically (Figure 7.2). To produce the horizontally oriented surface the procedure was the same as that used in previous experiments. The parallax or disparity signal was fed to the X input of the oscilloscope with a frequency such that one cycle of the signal occured for every frame of the raster (approximately 20msecs or 50Hz). This had the effect of introducing the same amount of horizontal relative motion or disparity to each line of the random dot pattern with the amount varying, in accordance with the desired profile, from the top to the bottom of the screen (Figure 7.6a). To produce a Cornsweet surface where the edge was oriented vertically, on the other hand, it was necessary that the parallax or disparity signal should be at a frequency such that one cycle of the waveform occured for every line of the raster (approximately 15kHz). In this case, the dots on each line of the pattern were shifted by different amounts from the left to the right of the pattern, according to the shape of the profile. From the top to the bottom of the pattern each column therefore moved by the same amount (Figure 7.6b). It is important to

(a)



(b)

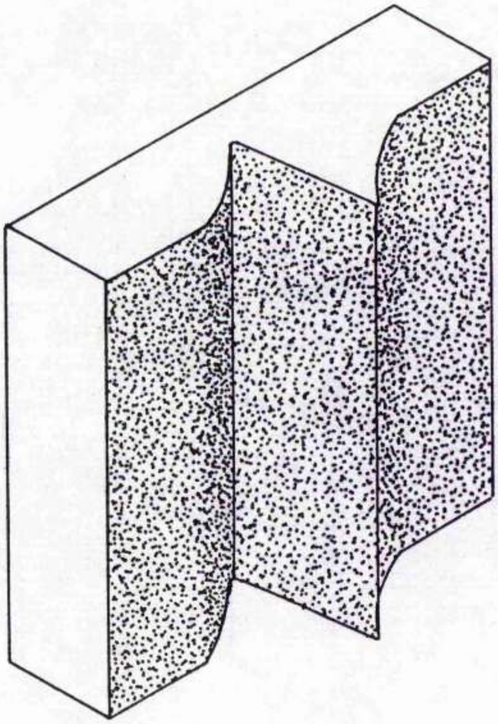
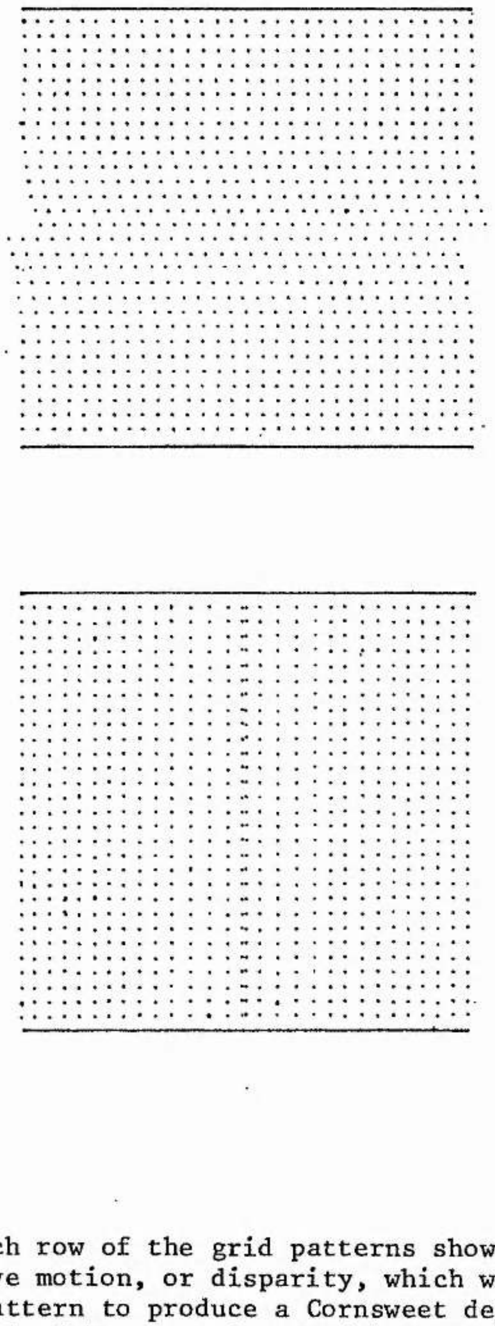


Figure 7.5.

The extent of the Cornsweet illusion was measured for both the depth surfaces illustrated here. The depth relationships within the surface are reversed in (b) with respect to (a). Measuring the strength of the illusion for both surfaces allowed any individual biases in setting the apparent frontoparallel to be compensated.



(a)

(b)

Figure 7.6.

The shifts in each row of the grid patterns shown here represent the amount of relative motion, or disparity, which was introduced into the random dot pattern to produce a Cornsweet depth surface oriented either horizontally (a) or vertically (b). In (a) each horizontal row was shifted horizontally by an amount which varied from the top to the bottom of the pattern in accordance with the desired profile. In (b) each vertical column was shifted horizontally by an amount which varied from left to right in accordance with the desired profile.

note that the direction of movement or disparity was still horizontal since the parallax or disparity signal was still fed to the X input of the scope. However, the direction in which the relative motion or disparity (and therefore depth) remained constant, was now vertical rather than horizontal.

There was also a simpler way of accomplishing the same effect and producing a vertically oriented Cornsweet surface. This was to reverse the scans of the raster so that the line and frame rate deflection signals were fed to the Y and X inputs, respectively, of the scope. When this was done the lines of the raster went from the top to the bottom of the pattern rather than from the left to the right. Therefore the original parallax or disparity signal at the slow frame rate (50Hz) now shifted each vertical line of the raster by the same amount and the amount varied from the left to the right of the pattern thus producing the pattern shown in Figure 7.6b. Again the direction of relative movement or disparity was still horizontal but the direction in which the amount of horizontal shift was constant was vertical. This latter method of producing a vertically oriented surface was the one actually employed in the present experiments.

To summarise, in order to produce a horizontally oriented Cornsweet depth surface, Figure 7.2a, a signal of the same shape as the Cornsweet profile, and at a frequency equivalent to the frame rate, was fed to the additional X input of the oscilloscope. For the parallax display this signal was continuously amplitude modulated according to the movement of the observer, while for the stereoscopic display the signal produced horizontal disparities between the two random dot patterns in the display. The high frequency line deflection signal and the lower frequency frame deflection signal were fed to the X and Y inputs respectively, in the normal way. To produce a vertically oriented Cornsweet surface, Figure 7.2b, the scan was reversed and the line and frame deflection signals were fed to the Y and X inputs respectively. The parallax or disparity signal was still fed to the additional X input to produce horizontal relative motion or disparity. The resultant distribution of relative velocities or disparities was like that illustrated in Figure 7.6b.

Three subjects took part in the experiment, one of whom was naive to the purpose of the experiment. A session consisted of two sets of eight trials each of which consisted of two repetitions of the four depth surfaces illustrated in Figure 7.4. The amplitude of the Cornsweet signal was inverted for the second set of trials. Four sessions were carried out for both parallax and stereoscopic depth conditions. In two of the sessions the depth surfaces were presented with the Cornsweet profile oriented horizontally and in the other two sessions they were presented with the profile oriented vertically. For each trial the observer was presented with one of the Cornsweet depth surfaces and asked to judge whether the flat areas, which flanked the spur-shaped change in depth, appeared to lie at the same distance. To aid these judgements the edges of the flanking areas were outlined with bright lines across the random dot pattern. If the flat areas did not appear to be equidistant, then the observer was required to adjust a potentiometer, which altered the relative depths of the flanks, until they did appear to lie at the same distance. While adjusting the relative depth of the flanks observers were asked to scan the whole depth surface in quick glances, to prevent the build-up of negative depth aftereffects. Null settings were typically reached within one minute of viewing and the amount of relative depth between the flanks at the null setting was recorded. There was a break of about 30 seconds between trials.

iii) Results

The results obtained for the three observers are shown in Figure 7.7 where the extent of the illusion is plotted as a function of the number of Cornsweet edges present in the depth surface. The results are shown for horizontally and vertically oriented Cornsweet surfaces both when the depth surfaces were specified by motion parallax and when they were specified stereoscopically. The results show essentially the same pattern in the parallax and stereo conditions. When the Cornsweet depth surface was oriented horizontally there was little illusory effect, although there was perhaps a small effect for the one cycle surface. However, when the surface was oriented vertically there was a very large Cornsweet illusion in the predicted direction, so that the two equidistant flanks of the profile appeared to lie at different depths from the observer. The flank which was attached to the part of the Cornsweet surface which sloped toward the observer appeared to lie closer than the flank which was attached to the part which sloped away. The size of the illusion reached 40% for vertically oriented surfaces indicating that, effectively, the amplitude of the faster changing component of the profile had to be reduced by 40% to cancel the illusory depth difference. The illusion decreased in magnitude as the number of edges in the depth surface increased, but it still remained substantial. Most observers showed a bias in setting the flanks to be equidistant when the one and two cycle surfaces were presented. This caused the extent of the illusion to vary when the depth amplitude of

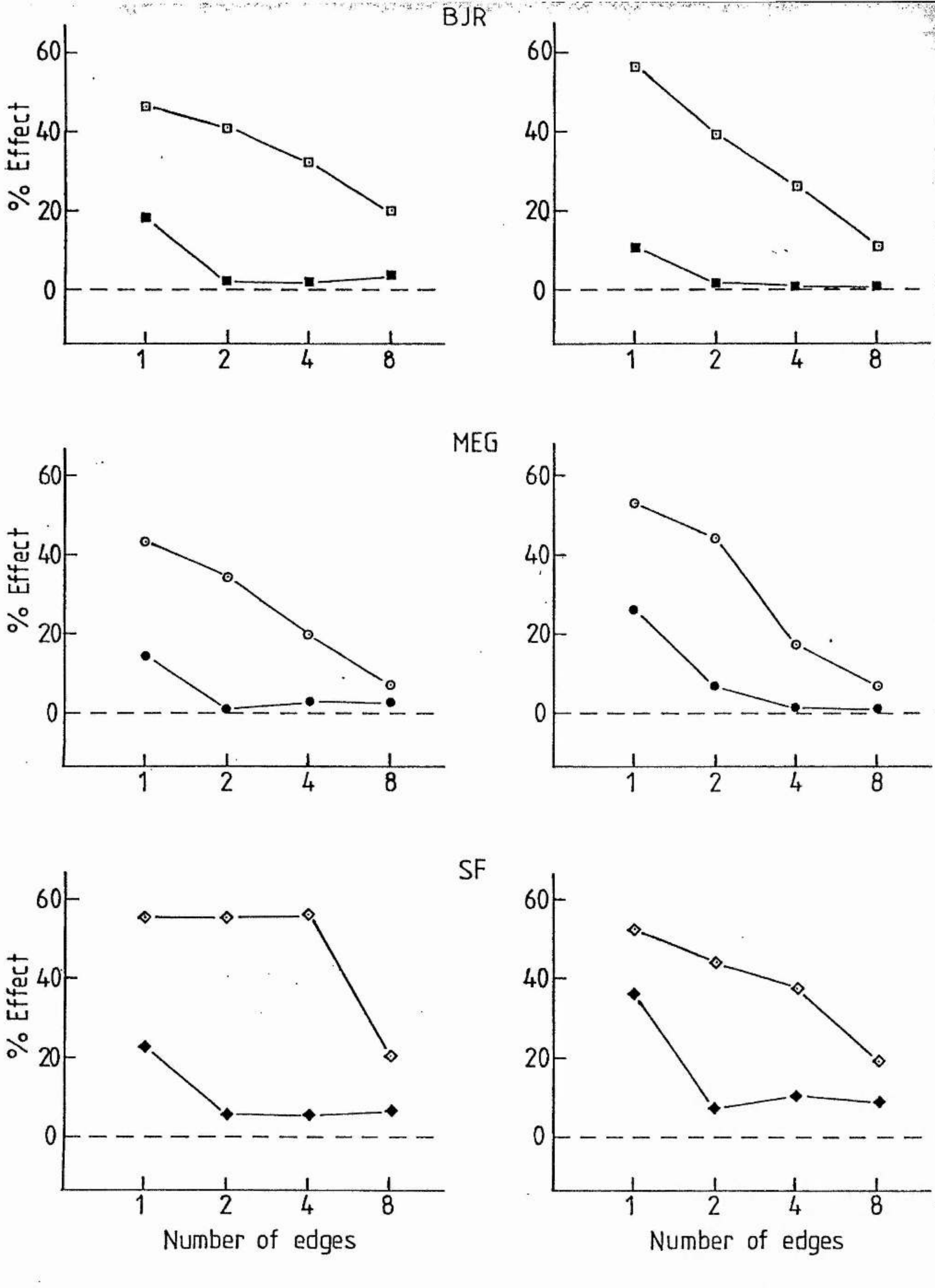


Figure 7.7.

The percentage strength of the Cornsweet illusion is plotted as a function of the number of Cornsweet edges in the depth surface. Data are shown for depth surfaces specified both stereoscopically and by motion parallax, for the three observers.

the surface was inverted. The data plotted in Figure 7.7, show the mean extent of the illusion for surfaces of both phases.

iv) A modified method

The results described above indicate that there is a striking anisotropy in the extent of the Cornsweet illusion perceived for horizontally and vertically oriented depth surfaces. This finding was unexpected and it was decided to replicate the experiment in a modified form which improved some aspects of the original display.

In the initial experiment, the rates of depth change, or depth frequencies, in the four Cornsweet surfaces were slightly different for the horizontal and vertical conditions, because of the size of the oscilloscope screens which were 25 degrees horizontally by 20 degrees vertically. Although this discrepancy was taken into account when the above data were plotted, it was decided that the illusion should also be measured using a square random dot pattern where the frequencies were identical in the two conditions. The use of a square pattern also ensured that differences in the horizontal/vertical dot size and spacing, which had been another potential artifact, were eliminated. To produce the square random dot pattern the the X and Y amplifiers were adjusted to be equal so that the raster was square. Other display characteristics were the same as those used in the initial experiment.

The second modification made in the present experiment was to use a more sophisticated method for producing the Cornsweet distortion signal. This method eliminated some spurious discontinuities in depth which had sometimes occurred at the centre edge of the profile with the previous method. These discontinuities arose from the use of a step function with a sharp edge, rather than a smooth ogive, to provide the fast changing component of the profile. In the modified method, the Cornsweet profile was directly produced by the sum of a slow and fast changing ogive (as illustrated in Figure 7.3) and the amplitude of the fast changing ogive could be directly adjusted by the observer. The profiles were chosen so that the slowly changing part of the profile remained unaltered as the amplitude of the fast component was varied, and so that there were no spurious discontinuities within the profile. When the amplitude of both components was equal the depth surface had the standard Cornsweet shape and the depth difference between the peak and trough of the surface was 8 min arc.

The procedure was similar to that used in the initial experiment. Observers adjusted the relative depth of the flat flanking areas until they appeared to be equidistant, while making rapid glances at the surface to avoid aftereffects. Cornsweet surfaces containing 1,2,4 or 8 edges (Figure 7.4) were used as stimuli, the extent of the illusion being measured in separate blocks for the different surfaces. Within each block the surfaces were presented eight times in both horizontal and vertical orientations, with the Cornsweet signal being inverted on alternate trials (Figure 7.5). As before, this reversed the depth amplitude within the surface. Measuring the effect for surfaces of both phases compensated for any observer bias in setting the apparent frontoparallel plane. The illusion was measured for two experienced observers for Cornsweet surfaces specified both by parallax and stereoscopic depth information.

v) Results

The results are plotted in Figure 7.8 where, again, the extent of the illusion in percentage terms is expressed as a function of the number of edges present in the surface. The pattern of results was essentially the same as that found in the initial experiment and occurred for both parallax and stereoscopic surfaces. There was little or no Cornsweet illusion when the depth surface was oriented with the Cornsweet edge horizontal, but there was a large illusory effect when it was oriented vertically. The strength of the effect decreased for vertically oriented surfaces when the number of Cornsweet edges in the surface increased. Again the data obtained for surfaces with normal and inverted amplitudes have been averaged.

vi) Discussion

Both these experiments demonstrate that there was a large depth illusion for surfaces with a Cornsweet profile, when the orientation of the sharp depth contour was vertical. The flat areas of the profile, which flanked the spur shaped change in depth and were physically equidistant, appeared to lie at different distances from the observer. The flank adjacent to the part of the surface which curved toward the observer, appeared to be nearer the observer than the flank attached to the part which curved away. This depth illusion is, therefore, directly analogous to the brightness illusion found for patterns with a Cornsweet luminance profile. However, the Cornsweet illusion for depth is only observed when the depth surface is oriented vertically and is not present for a depth surface, of identical shape, which is oriented with the sharp contour lying horizontally.

The size of the anisotropy in the extent of the Cornsweet

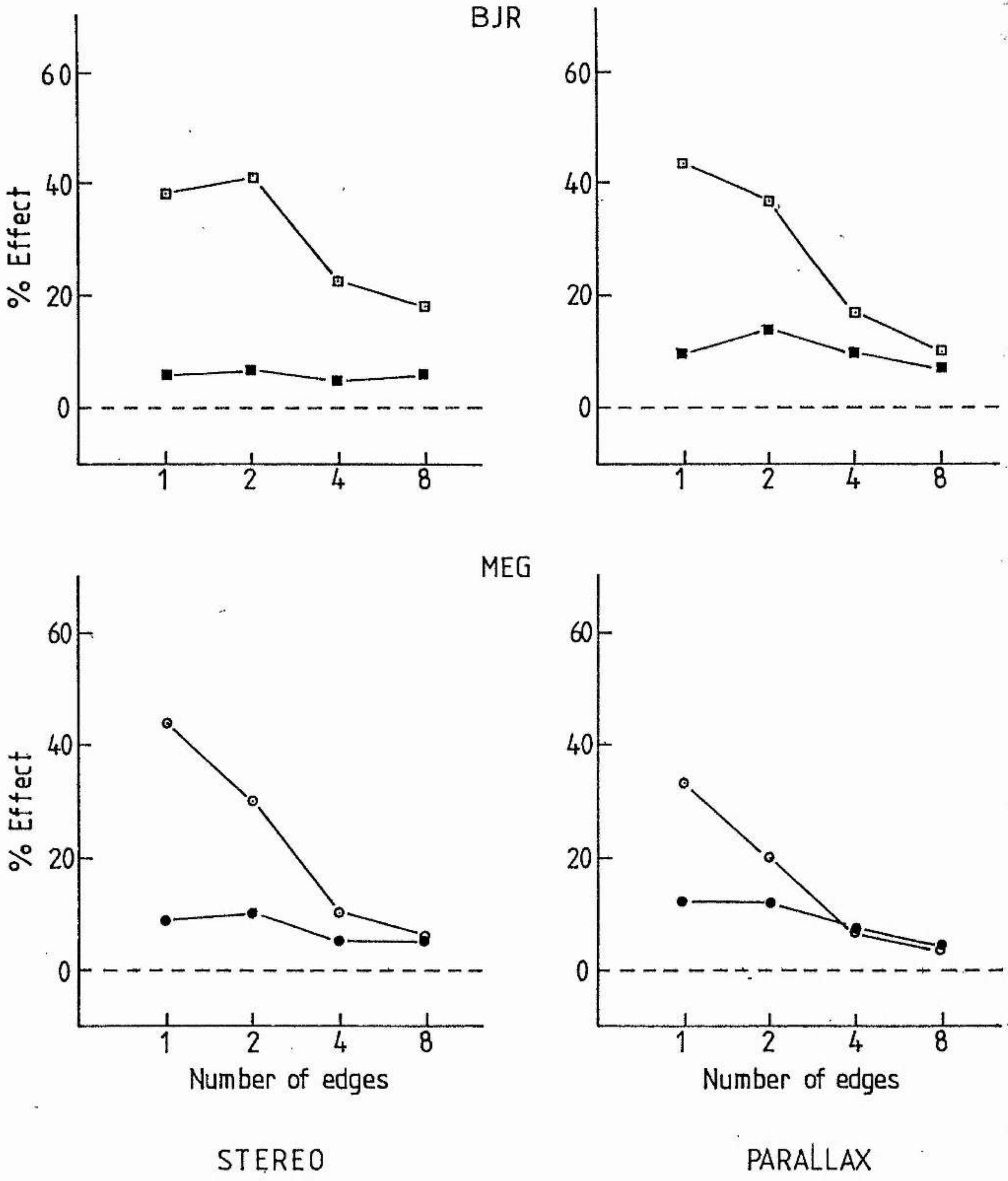


Figure 7.8.

The Cornsweet depth illsuion measured with a modified display. The percentage strength of the illusion is plotted as a function of the number of Cornsweet edges in the depth surface. Data for the two observers, BJR and MEG, are shown for depth surfaces specified both stereoscopically (left) and by motion parallax (right).

illusion is striking. For the depth surface containing two cycles of the Cornsweet profile, the mean strength of the effect was 40% for vertically oriented surfaces and only 5% for horizontally oriented surfaces. The reason for the anisotropy is not obvious. For stereoscopic depth surfaces alone, it could perhaps have been attributed to the inherent anisotropy of the stereoscopic system, since depth is only processed from horizontal disparities (although vertical disparities seem to be involved in fusion and, possibly, the computation of absolute disparity (Ogle, 1955; Mayhew and Longuet-Higgins, 1982)). However, since the anisotropy occurs to the same extent for depth surfaces specified by motion parallax information, this explanation seems unlikely. Motion parallax does not depend on the relative movement being in a horizontal direction and so there is no a priori reason to expect an anisotropy in the processing of parallax information. It seems probable, therefore, that the anisotropy reflects some general principle of depth processing.

As mentioned above, the Cornsweet illusion in the luminance domain is usually attributed to the relative insensitivity of the visual system to gradual changes in luminance over space. By an analogous argument it might be hypothesised that the Cornsweet depth illusion reflects a relative insensitivity to gradual changes in depth over space. If such an argument is correct, then the insensitivity should be reflected in other psychophysical measures such as the sensitivity function for detecting corrugated depth surfaces of different depth spatial frequencies.

The experiments reported in chapter 4 described the sensitivity functions which were obtained for corrugated depth surfaces specified by both motion parallax and stereopsis. These sensitivity functions were measured for depth surfaces which were sinusoidally modulated in depth from the top to the bottom of the surface, and so the depth corrugations were oriented horizontally. It was found that peak sensitivity occurred for corrugated surfaces of 0.2-0.4cyc/deg and thresholds increased at both higher and lower spatial frequencies. Hence, for horizontally oriented surfaces there is a decline in sensitivity for very gradual changes in depth and so a Cornsweet illusion should be predicted. However, the sensitivity function for horizontal depth corrugations only begins to fall off below 0.2 cycles per degree and it is possible that the depth surfaces used to investigate the Cornsweet illusion did not contain sufficiently slow changes in depth to allow this fall-off to produce the illusion. Such an argument is supported by the fact that there did appear to be a small illusion for the one cycle, horizontally oriented, Cornsweet surface which contained the slowest changing depth contours. The argument predicts that a horizontal Cornsweet surface with sufficiently gradual depth slopes would produce a strong illusion, however, such a surface would have to extend over a large spatial area (greater than 40 degrees of visual angle. Apart from the practical difficulties of displaying such a surface, the two flanking areas of the profile would then be separated by a large distance which would make the depth matching task very difficult.

Another prediction from the above argument can be tested more directly. Since the Cornsweet illusion occurs for vertically, but not for horizontally oriented surfaces, the sensitivity function for detecting vertically oriented depth corrugation should differ from the sensitivity function for detecting horizontal corrugations. That is, the anisotropy in the extent of the Cornsweet illusion, should also be reflected in an anisotropy in the thresholds for detecting corrugated depth surfaces of the same spatial frequencies but of different orientations. This prediction was investigated in the subsequent experiment.

A further point can be made with respect to the spatial interactions which presumably underly both the fall-off in sensitivity to low spatial frequency corrugations and the presence of the Cornsweet illusion. The large simultaneous contrast effects found for horizontally oriented surfaces, and described in the last chapter, clearly indicate that spatial interactions are important for processing depth change in these surfaces. It is likely that these interactions are inhibitory and are reflected in the low frequency fall-off in sensitivity for horizontally corrugated surfaces. Although, the extent of the simultaneous contrast effects reported in the last chapter have not been measured for vertically oriented depth surfaces, informal observations have shown that the effects are still present and may be larger than those observed for horizontally oriented surfaces. This suggests that spatial interactions are involved in processing the depth changes within vertically, as well as horizontally, oriented surfaces. Moreover, the fact that simultaneous contrast effects occur for both horizontally and vertically oriented surfaces but that no Cornsweet illusion is observed for horizontally oriented surfaces, suggests that any explanation for the Cornsweet depth illusion must invoke additional factors than those which give rise to the simultaneous contrast effects. For example, if the effect is due to spatial interaction in the depth domain, there must be differences in the nature of the spatial interactions involved in perceiving horizontally and vertically oriented depth surfaces.

In this regard it is possible that the anisotropy does not reflect differences in the nature of the spatial interactions, but rather reflects a difference in an additional process which is also involved in producing the illusion. In the luminance domain, it has been suggested that the Cornsweet illusion involves a process which extrapolates the illusory depth information provided by the changing part of the profile across the surrounding flanking areas. This is thought to be necessary since the whole flanking area is perceived to be at a different brightness (Ratliff, 1965). It is possible that a similar process is involved in the Cornsweet depth illusion. It is not clear, however, that such a process is strictly necessary to explain the illusion. If the depth system does not respond well to flat surfaces, which after all are examples of very low frequency depth change, and if the spatial extents of depth processing units are large then an extrapolation effect would be unnecessary. On the other hand, if such a process was involved in the Cornsweet depth illusion, then the anisotropy could occur at that level. If this were the case, then similar anisotropies would not be expected to occur for other psychophysical measures such as threshold detection, which presumably do not involve any extrapolation process.

7.2 Sensitivity to horizontal and vertical depth corrugations.

To ascertain whether the anisotropy found in the extent of the Cornsweet illusion for visual depth, was accompanied by a similar anisotropy in detection thresholds, sensitivity functions for detecting horizontal and vertical depth corrugations were measured for depth surfaces defined by both motion parallax and stereopsis. The argument outlined above, suggested that there was no Cornsweet illusion for the horizontally oriented stimuli because they did not contain components which were of sufficiently low frequency to be affected by the low frequency fall off that occurs in the sensitivity function for horizontal corrugations. Since the illusion was found to occur for the vertically oriented Cornsweet surfaces, a necessary prediction would be that the sensitivity function for vertical corrugations falls off more rapidly than that for horizontal corrugations and, perhaps, that the peak sensitivity occurs at a higher frequency.

In previous experiments sensitivity functions had been measured for depth surfaces which were sinusoidally modulated in depth in one dimension. In these surfaces the orientation of the depth corrugations, or contours was horizontal. This type of one-dimensional depth modulation had been specifically chosen to avoid possible confounding factors that occur when surfaces are modulated to produce vertical depth contours. Surfaces with vertical depth contours theoretically provide three different types of information about depth when they are viewed during horizontal lateral movement. Besides the horizontal relative motion between different points on the surface (parallax motion), occlusion effects will also be observed if there is a sharp change in depth within the surface. As the observer moves laterally a sharp vertical depth contour will occlude or reveal other parts of the surface. Finally, as the observer moves laterally while viewing a vertically oriented slope in depth, for example, the angle of the slope with respect to the observer will change. Hence, if the surface is evenly textured, the density of texture will change as the observer moves, thus providing another potential source of depth information. For a horizontally oriented slope, on the other hand, the orientation of the depth contour is parallel to the direction of movement and so the angle of slope with respect to the observer does not change as the observer moves laterally. The different types of depth information available during horizontal lateral movement, while viewing a vertically oriented depth surface, are shown in Figure 7.9. If the extent of observer movement is not large and the surface is continuous with relatively shallow depth changes the occlusion effects can be eliminated. However, the horizontal relative movement between parts of the surface at different depths will always be accompanied by changes in texture density. This did not, however, present a major problem for the present experiment, since the changes in texture density from different viewing positions were generally too small to be noticed by the observers.

In the present experiment, thresholds for detecting depth surfaces which were sinusoidally modulated in one dimension, were measured as a function of the spatial frequency of the depth corrugation. Thresholds were measured both when the corrugated depth surfaces were oriented horizontally, so that the corrugations lay parallel to the direction in which the observer was moving, and when they were oriented vertically with the corrugations orthogonal to the direction of motion.

i) Method

The usual motion parallax and stereoscopic displays were used to present depth surfaces specified by relative motion or binocular disparities. Sinusoidally modulated depth surfaces of six different

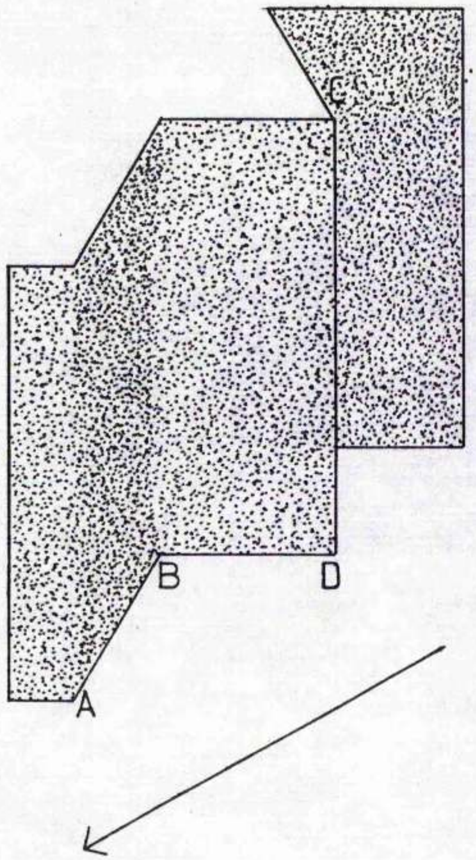


Figure 7.9.

Three potential sources of information about depth are available when an observer moves horizontally while viewing a vertically oriented depth surface. For the surface shown, in addition to the relative velocity between A and B (motion parallax), the surface at C becomes progressively occluded. Moreover, a difference in texture density between the surfaces AB and BD occurs because they are at a different angle with respect to the observer. The texture density within each surface changes as the angle of slope with respect to the observer changes during movement.

spatial frequencies were used as stimuli. These were presented with the corrugations oriented either horizontally or vertically. In both cases, the parallax or disparity signal was introduced into the X input of the oscilloscope. However, to produce vertical corrugations the line and frame signals which produced the raster were reversed so that they went to the Y and X inputs respectively. As described above for the Cornsweet depth surface, this ensured that the line of constant relative motion or disparity, and hence depth, was oriented vertically rather than horizontally. The different patterns of relative motions or disparities which were produced when horizontal and vertical corrugations were presented are illustrated in Figure 7.10, for a surface containing one cycle of a sinusoidal corrugation. In this figure, the arrows show the change in position of dots in a rectangular grid as the observer moves from right to left while viewing either a horizontally (a) or vertically (b) oriented depth corrugation. The arrows also represent the disparities of individual points which are present in a stereoscopic view of each surface. In the actual experiment, the pattern was a totally random array of dots, rather than a rectangular grid, which carried the pattern of relative motion or disparity illustrated.

Thresholds were measured using an ascending method of limits. The peak to trough depth amplitude of the corrugated surface was gradually increased until the observer could just perceive that the surface was corrugated, and could also report the phase and number of

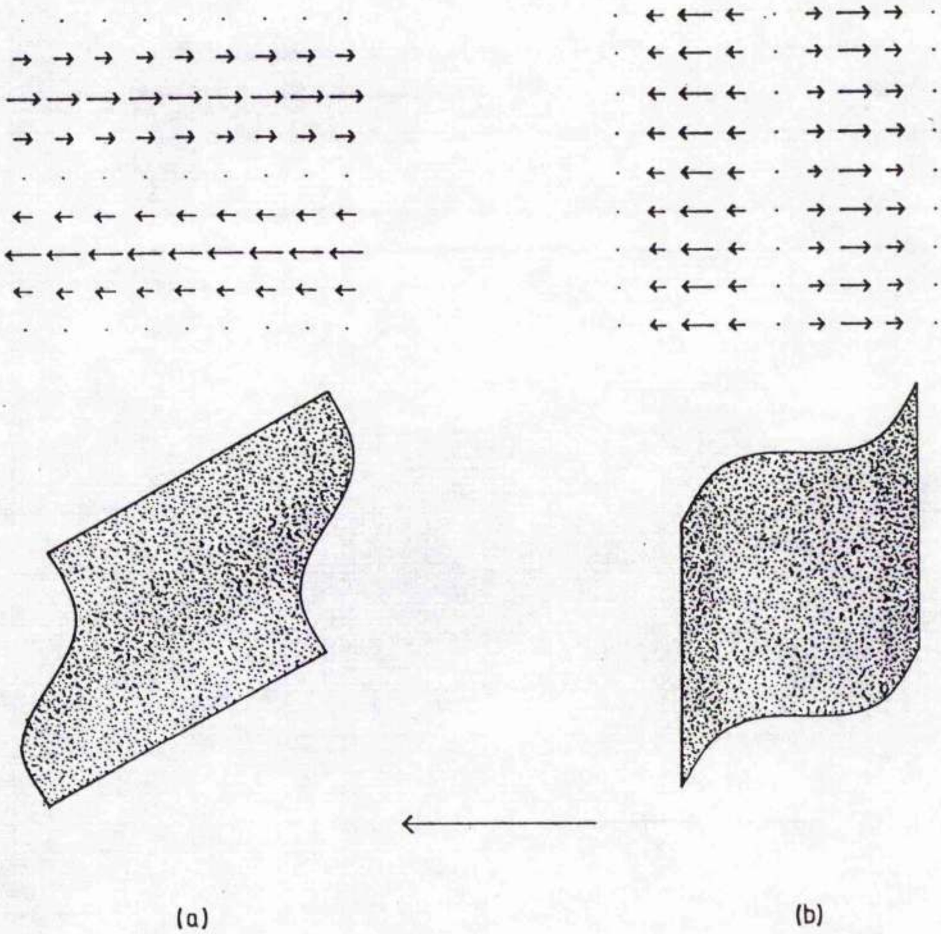


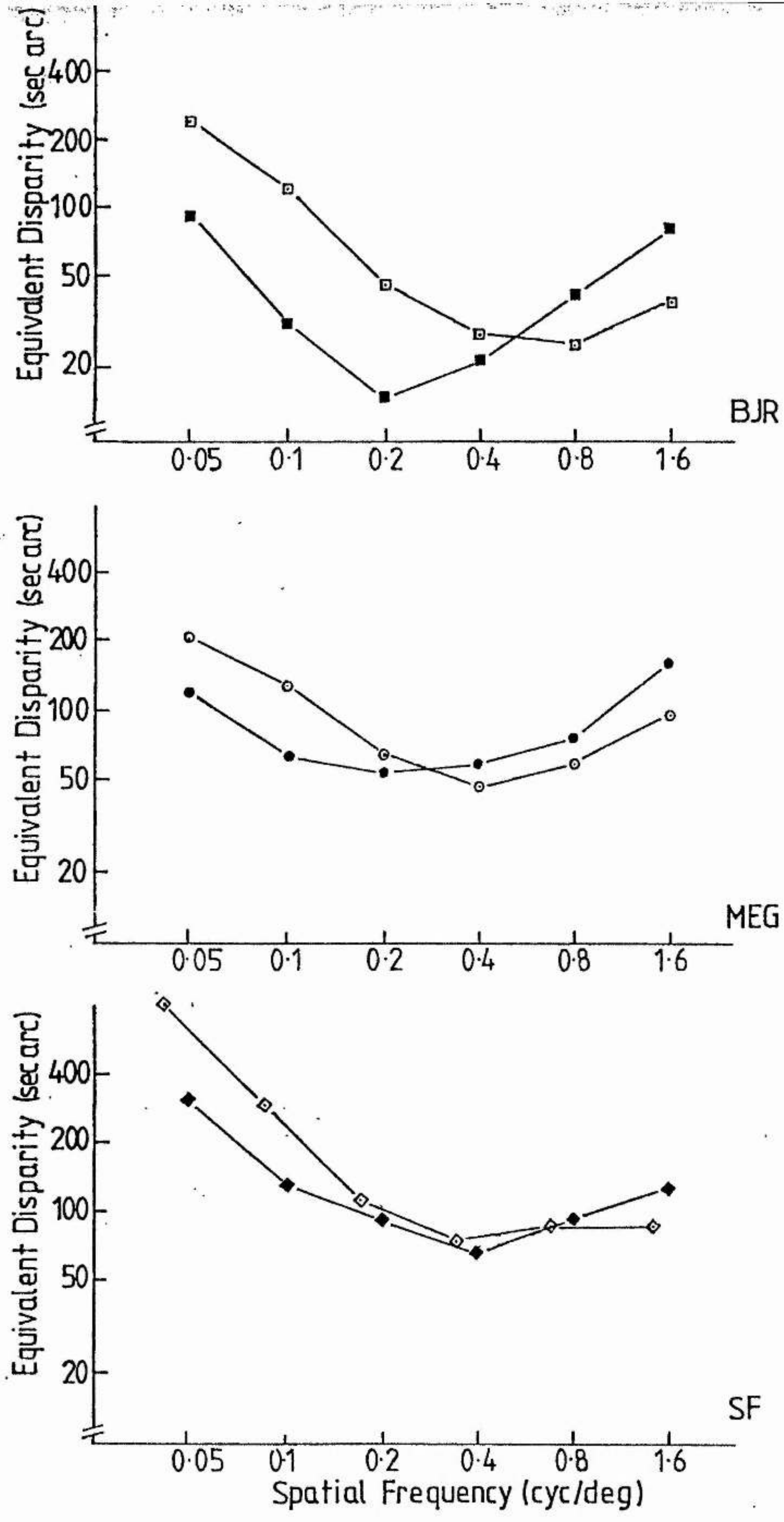
Figure 7.10.

The different patterns of relative motion or disparity which were used to produce either a horizontally (a) or vertically (b) oriented depth surface which consisted of a single cycle of a sinusoidal corrugation. The arrows represent the amount and direction of velocity, or the amount of disparity, for different parts of the random dot pattern.

cycles of the corrugation. When observers could just perceive the surface they pressed a key which terminated the trial and a flat random dot surface was presented during the inter-trial interval. The peak to trough amplitude of the surface when the key was pressed was taken as a measure of threshold. This threshold value determined the starting amplitude for the next presentation of the corrugated surface of that spatial frequency. A session consisted of thirty trials which comprised ten settings at each of three spatial frequencies presented in random order. For each frequency the phase of the corrugation was reversed on alternate trials. Thresholds for the other three frequencies were measured in the subsequent session. Thresholds for horizontally and vertically oriented surfaces were measured on separate days. After all the thresholds had been measured for parallax depth corrugations, the whole experiment was repeated for stereoscopic surfaces. Before the experimental sessions, several practice sessions were run, mainly with vertically oriented corrugations, to allow observers to become used to viewing depth surfaces in this orientation. Three observers took part in the experiment, one of whom was naive as to its purpose.

ii) Results

The threshold data for detecting depth corrugations for parallax surfaces oriented either horizontally or vertically, are plotted in Figure 7.11, for the three observers. The pattern of results found for all observers was similar. For horizontally oriented parallax corrugations the sensitivity function peaked at around 0.2 to 0.4 cyc/deg and sensitivity fell-off for frequencies higher and lower than this. This pattern was similar to that found in previous threshold



PARALLAX

Figure 7.11.

Sensitivity functions for detecting horizontally and vertically oriented parallax depth corrugations. Data are shown for the three observers. The equivalent peak to trough disparity at threshold is plotted as a function of the spatial frequency of the depth corrugation. Open symbols show data for vertically oriented corrugations, closed symbols data for horizontally oriented corrugations.

experiments using these stimuli (see Figure 4.4). The most striking aspect of the data was the sensitivity functions observed for vertically oriented corrugations, where there was a very large decrease in sensitivity at the low frequency end of the function. For depth spatial frequencies below 0.2 cyc/deg the thresholds for vertical corrugations were considerably higher than those for horizontal corrugations, by roughly a factor of two. In the high frequency region, however, the opposite relation occurred. Here thresholds were slightly lower for vertical than for horizontal corrugations. The region of peak sensitivity also seemed to be shifted to a higher spatial frequency for vertical corrugations.

For depth corrugations specifed by stereoscopic information, the pattern of results appeared to be slightly different. The data are plotted in Figure 7.12. Over a wide range of frequencies, thresholds for detecting vertically-oriented corrugated surfaces were very much greater than those for detecting horizontal corrugations. This was particularly true for corrugated surfaces of low spatial frequencies where the difference in threshold could be as much as a factor of eight. Differences in horizontal/vertical thresholds were, therefore, much greater for low spatial frequencies, and in this respect the results were similar to those found for parallax corrugations. However, there was also an overall insensitivity to vertically oriented corrugations when the depth was specified stereoscopically.

iii) Discussion

The sensitivity functions for detecting sinusoidal depth modulations oriented either horizontally or vertically, clearly

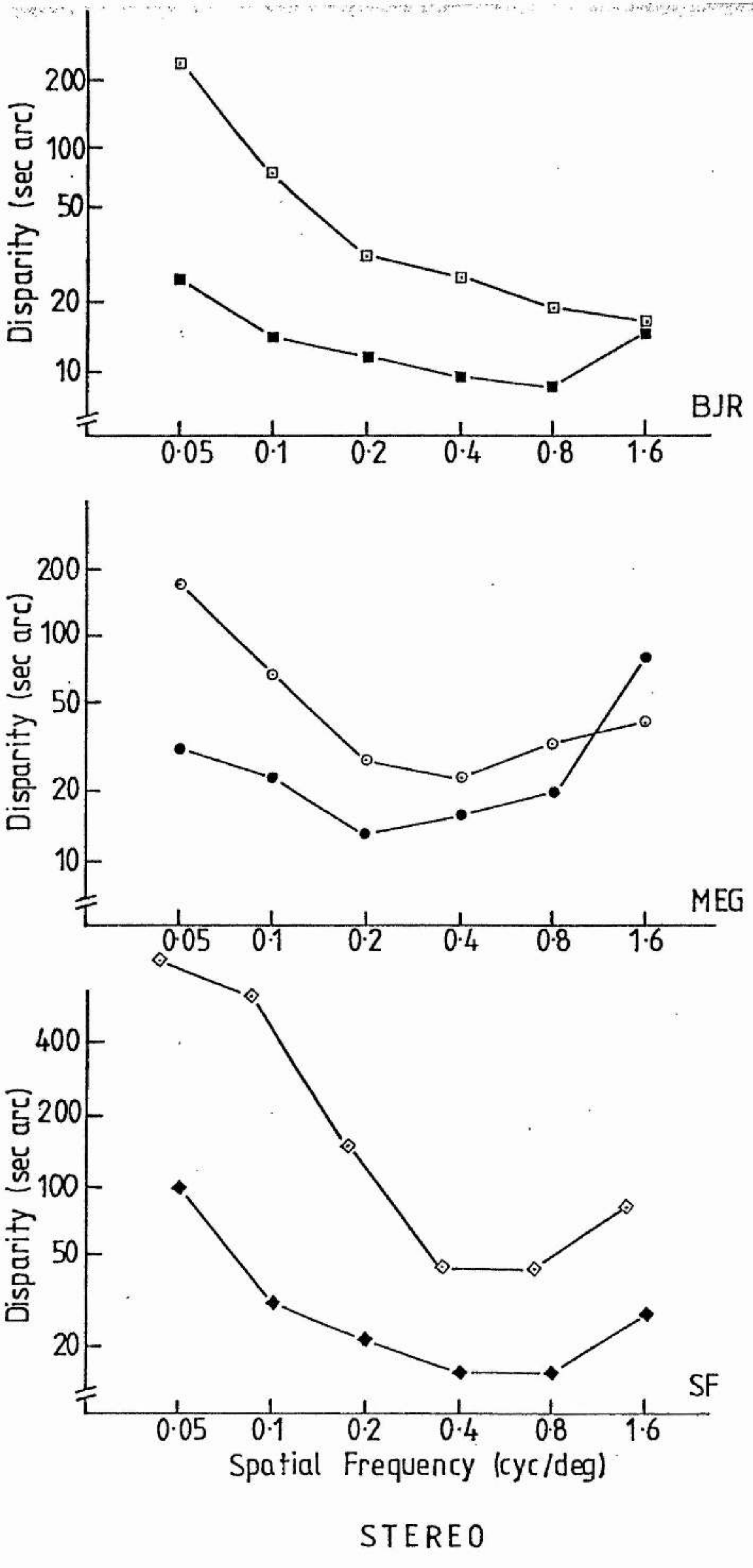


Figure 7.12.

Sensitivity functions measured for the three observers, for detecting horizontally and vertically oriented stereoscopic depth corrugations. The peak to trough disparity at threshold is plotted as a function of the spatial frequency of the depth corrugation. Open symbols - vertical corrugations, closed symbols - horizontal corrugations.

demonstrate that an anisotropy occurs in sensitivity to depth modulation. Except at high spatial frequencies, thresholds for detecting vertically oriented corrugations were much higher than those for detecting horizontal corrugations. Moreover, the relative sensitivity difference between corrugations with low and peak spatial frequencies was much larger for vertical corrugations and the region of peak sensitivity appeared to be shifted slightly to higher spatial frequencies.

Thresholds obtained for stereo surfaces showed an even larger anisotropy than parallax depth thresholds. In Figure 7.13, the sensitivity functions for stereoscopic surfaces, which were plotted in Figure 7.12, have been shifted vertically relative to each other, as indicated by the dotted line. (The functions have been shifted, arbitrarily, by a factor of 2.5 for observers BJR and SF and by a factore of 1.7 for observer MEG). It can be seen that, with this manipulation, the horizontal/vertical differences in stereoscopic thresholds are very similar to those observed for parallax surfaces (see Figure 7.11). This suggests that, besides the general relative insensitivity to low frequency vertical depth corrugations shown by both depth processes, the stereoscopic system shows an additional insensitivity to vertical corrugations which is independent of frequency.

In line with the argument presented earlier, these results confirm the prediction that the anisotropy found in the extent of the Cornsweet illusion is accompanied by similar anisotropies in other psychophysical tasks. In particular, the observation that the sensitivity difference between low and peak spatial frequencies is much

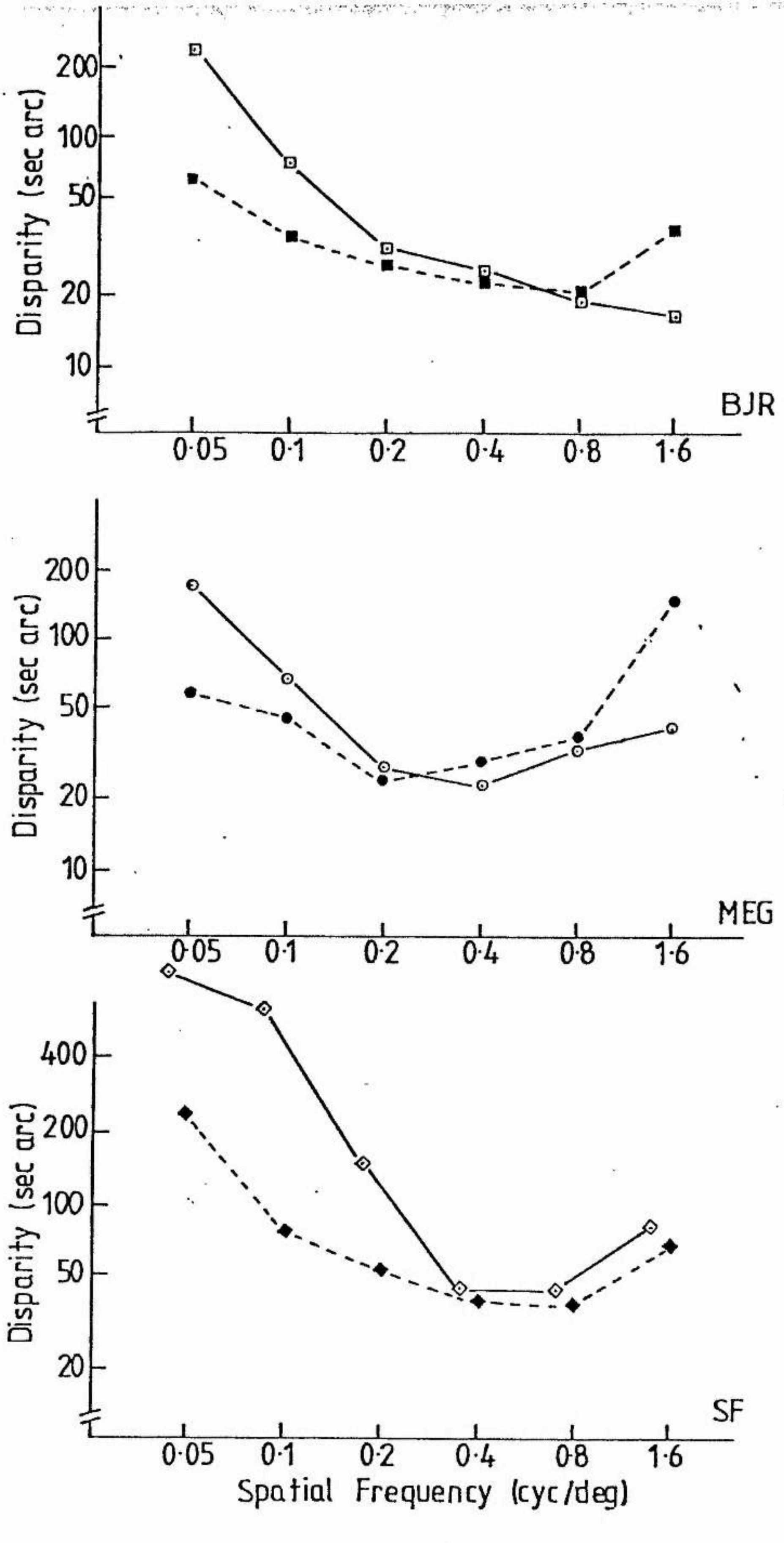


Figure 7.13.

The sensitivity functions for detecting stereoscopic depth corrugations which were plotted in Figure 7.12 have been replotted with the data for horizontally oriented corrugations (closed symbols) shifted up by a factor of 2.5 for BJR and SF and by a factor of 1.7 for MEG.

larger for vertical corrugations is consistent with an explanation of the Cornsweet illusion in terms of a relative insensitivity to low spatial frequencies. It seems that the low frequency fall off in sensitivity to depth modulation for horizontal surfaces is not large enough to produce the Cornsweet depth illusion which is observed for a vertically oriented surface.

The Cornsweet illusion is, of course, a suprathreshold depth effect and the sensitivity measures used in the experiment just described are threshold measures. The exact relationship between threshold and supra-threshold characteristics of visual processing systems is difficult to determine and is not necessarily a direct one (Braddick et al., 1978; Georgeson and Sullivan, 1975). It was therefore decided to investigate whether an anisotropy in sensitivity could also be measured using a supra-threshold technique. In particular, a further experiment was carried out to determine whether an anisotropy would be evident in a task which required observers to match the perceived depth of both horizontally and vertically oriented surfaces, which were sinusoidally modulated in depth with an amplitude well above threshold.

7.3 Matching the perceived depth of horizontal and vertical depth corrugations.

A simple matching task was carried out to investigate whether there was a supra-threshold anisotropy in sensitivity for depth modulations specified either stereoscopically or by motion parallax. Observers were required to directly match the perceived depth of horizontally and vertically oriented depth surfaces which were sinusoidally modulated in depth with the same spatial frequency. From the results obtained for threshold sensitivity, it was expected that the perceived depth of a vertical corrugation would be less than the perceived depth of a horizontal corrugation although, physically, they both contained the same amplitude of peak to trough depth. Moreover, this effect was expected to occur to a greater extent for corrugated surfaces of low spatial frequencies and to be less in evidence, or non-existent, for corrugations of medium or higher spatial frequencies.

i) Method

The characteristics of the motion parallax and stereoscopic displays used to display the depth surfaces were, essentially, the same as those used in previous experiments. Vertical and horizontal corrugations were again produced by changing over the line and frame deflection signals, while the distortion signal remained the same. Since in this experiment it was necessary to swap rapidly between horizontal and vertical corrugations to allow a match to be made, the apparatus was modified slightly so that the line and frame signals could be changed over by depressing a single switch. In addition, the size of the pattern was reduced so that the 256 by 256 array occupied an area which was 20 degs square. This was done by adjusting the gain of the X and Y amplifiers to be equal, so that the raster was square. This modification ensured that the dot size and spacing were identical along both the rows and columns of the random dot pattern and that a corrugated surface containing four cycles across the pattern was of the same spatial frequency as one containing four cycles down the pattern. As a control, observers checked that no difference could be perceived in a flat random dot surface when the raster was reversed.

On each trial, the observer was presented with a horizontally corrugated depth surface of a particular spatial frequency. After ten seconds, the random dot pattern was blanked out for two seconds and then a vertically corrugated surface of the same spatial frequency was presented for another ten seconds. This was again followed by a two second blank period and the whole sequence was repeated ten times. The raster was reversed during the blank period, when no pattern was visible, so that the sudden change in the orientation of the pattern could not be perceived. The observers task was to adjust the peak to trough depth amplitude of the vertical depth corrugation, so that its perceived depth was equal to that of the horizontal corrugation, which was presented with a fixed amplitude. To do this, the observer adjusted a control which varied the overall amount of relative movement, or disparity, in the vertical corrugation while leaving the horizontal amplitude unchanged. In the case of parallax, the peak to trough amplitude of the horizontally corrugated surface was equivalent to 4 min arc of disparity, while for stereoscopic matching it was 2 min arc. The observer was required to make the match within the ten presentation cycles and was asked to scan over the whole surface while making the match, to ensure that negative aftereffects did not build up. During each session two matches were obtained for horizontal and vertical corrugations of six spatial frequencies. Two observers took part in the experiment and two sessions were carried out for both parallax and stereoscopic depth surfaces.

ii) Results

The depth in the vertical corrugation that was matched with the standard depth of the horizontal corrugation was expressed in terms of the ratio of the matched peak to trough depth to the standard peak to trough depth. This ratio is plotted as a function of the spatial frequency of the depth corrugation in Figure 7.14. Figure 7.14a shows the data for the two observers, for depth surfaces specified by motion parallax information, while Figure 7.14b show the data obtained with stereoscopic surfaces. For parallax surfaces, the matched depth of the vertical corrugation was greater than the standard depth of the horizontal corrugation when the spatial frequency of the corrugation was below 0.2 cyc/deg. For corrugated surfaces of 0.05 cycles per degree, for example, the two corrugations were perceived to be at the same depth only when the physical depth of the vertical corrugation was double that of the horizontal corrugation. However, above 2 cycles per degree, the matched depth of the vertical corrugation was slightly less than the standard depth. In the stereoscopic matching task, on the other hand, it was found that for corrugated depth surfaces of 0.2 cyc/deg and above, the matched depth of the vertical surface was very close to the physical depth present in the horizontal surface. However, as for parallax surfaces, at lower spatial frequencies the vertical peak to trough depth needed to match a horizontal depth of 2 min arc was greater than 2 min arc. In fact, for corrugations of 0.05 cyc/deg nearly 8 min arc of depth was needed to match the standard 2 min arc, thus representing a relative insensitivity to vertical corrugations of about a factor of four. The anisotropy at low spatial frequencies found in the present matching task was, therefore, greater when the depth surfaces were specified stereoscopically than when they were specified by parallax information. This is similar to the slightly different pattern of anisotropies found in the threshold

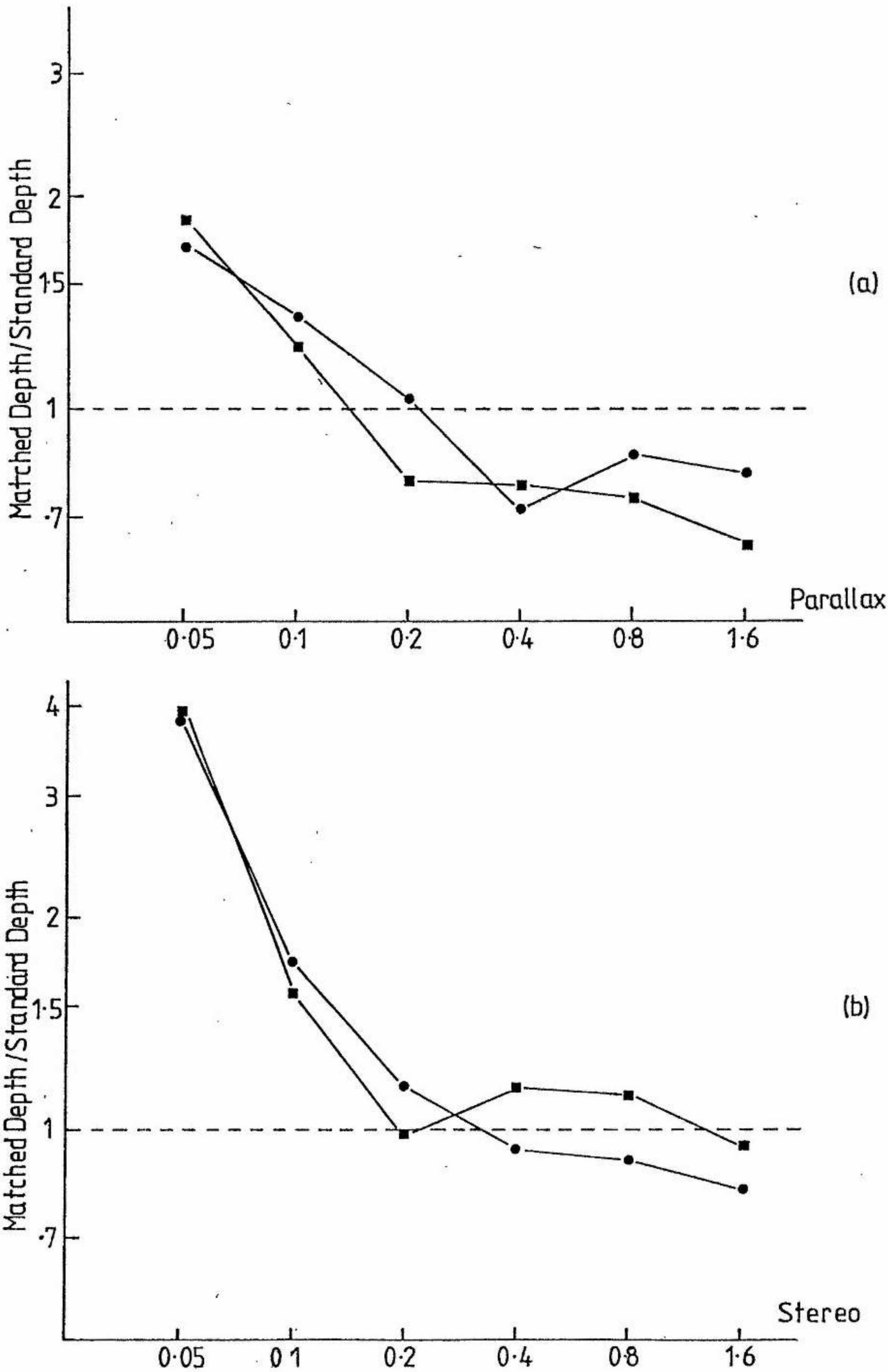


Figure 7.14.

The ratio of the matched depth of a vertical corrugation to the standard depth of a horizontal corrugation is plotted as a function of the spatial frequency of the corrugation. Data are shown for observers MEG (●) and BJR (■) for parallax (a) and stereo (b) depth surfaces.

experiments described previously.

7.4 General discussion.

The experiments reported in this chapter show that there are large anisotropies in the processing of depth information. At threshold, sensitivity to sinusoidal depth modulations of low spatial frequencies is much greater for horizontally than for vertically oriented surfaces. This difference in horizontal/vertical sensitivity for low frequency corrugations is also observed for surfaces which are considerably above threshold. In order to match the perceived peak to trough depth of a horizontal corrugation, the vertical corrugation has to contain up to four times the physical depth of the horizontal corrugation. These differences in sensitivity may form the basis for the Cornsweet illusion for visual depth which also shows an anisotropy. In the Cornsweet illusion, which is a supra-threshold effect, large illusory depth differences, between equidistant areas, are perceived when the Cornsweet depth surface is oriented vertically but not when the surface is oriented horizontally (Rogers and Graham, 1982b).

These results raise the question of the underlying reason for the anisotropies. Since they occur for depth surfaces specified by parallax information as well as those specified by binocular disparities, they are unlikely to be due to any inherent anisotropy of the stereoscopic system (because of its reliance on horizontal rather then vertical disparities). An anisotropic factor unique to stereopsis might, however, account for the slightly different pattern of threshold anisotropy found for stereoscopic surfaces. This difference seemed to be due to an additional anisotropic component which attenuated sensitivity to vertical stereo corrugations regardless of frequency. Alternatively, this component may have been due to an increased familiarity with horizontally-oriented stereo surfaces. The general pattern of vertical-horizontal differences at low but not at high spatial frequencies of depth modulation occured for both stereoscopic and parallax depth surfaces and was evident at both threshold and supra-threshold levels.

One possible explanation of the anisotropy is that the spatial interactions which are assumed to underly the processing of depth change are not circularly symmetric. That is, that the extent of spatial interactions in one direction is greater than that in the other. To explain the greater insensitivity to vertical corrugations, the amount or extent of inhibitory interactions between adjacent areas would have to be greater in a horizontal direction than in a vertical direction. This might be due to the presence of asymmetric depth receptive fields which have a smaller inhibitory region vertically than horizontally, or perhaps to a greater number of oriented receptive fields, with inhibitory flanks rather than surrounds, whose preferred orientation was vertical. This anisotropy would then only be present for large receptive fields. Mechanisms responsive to high spatial frequencies would perhaps show a more symmetric organisation and might process depth information in a rather different manner from the large depth receptive fields.

An alternative explanation is that the the anisotropy does not reflect any difference in the extent of horizontal/vertical spatial interactions within the depth processing systems, but rather results from the different patterning, over local areas, of the relative velocities or disparities which specify horizontally and vertically corrugated surfaces. As illustrated in Figure 7.10, for horizontally oriented corrugations the pattern of relative velocities or disparities which simulates a single cycle of a horizontal depth modulation can be characterised as a shearing motion between horizontal bands of the surface. The pattern produced by a vertically oriented corrugation, on the other hand, can be characterised as a one-dimensional expansion and contraction within vertical bands of the surface. If the processing of depth information depends on processing the different patterns of velocities, or disparities, over local areas of space, than the observed anisotropies might result because one of these patterns is easier to process than the other. In particular, to explain the anisotropy found here, the shear transformation would have to be easier to pick up than the expansion pattern. Since the anisotropy occurs for corrugations of low, but not high, spatial frequencies it would also be necessary that the difference in ease of processing between shear and expansion transformations only occurs when the shear or expansion occurs over a relatively large area of space. This would be the case if the mechanisms which extract the local transformations have a minimum receptive field size of, say, a degree or so. Then, at high spatial frequencies the area over which the local transformation occurs would be too small for the pattern to be registered. If this is the case, then another type of process, or mechanism, would need to be invoked to explain the ability to perceive depth surfaces of high spatial frequencies.

As discussed in chapter 2, the idea that the processing of parallax depth is based on picking up different local patterns of velocities plays a major role in computational theories of motion parallax. In particular, local mechanisms to detect the components of shear and expansion have been suggested by Longuet-Higgins and Prazdny (1980) and by Koenderink and van Doorn (1976). The different horizontal and vertical patterns of velocities produced in the above experiments would predominantly stimulate different types of these mechanisms. For example, in the physiological model suggested by Clocksin (1980a; 1980b), and illustrated in Chapter 2, the existence of two types of higher level receptive fields are postulated. In one, the direction preference of the component velocity sensitive mechanisms is in the same direction as the axis of the receptive field, and, in the other, their preferred direction is orthogonal to the orientation of the recptive field. The former type of receptive field would predominantly be used in picking up local expansion/contraction, while the latter would be used in picking up local shear. A difference in the number or effectivenes of these two types of mechanism would then account for the anisotropy. Expressed in more abstract terms, the anisotropy would then reflect the greater difficulty in computing the spatial velocity differentials in a direction parallel, rather than orthogonal, to the direction of the velocity.

It is impossible to disentangle these two possibilities for stereoscopic depth which depends on horizontal disparities. However, parallax information does not have to be restricted to horizontal relative motions. When an observer moves vertically in the environment, or when an object moves up and down in front of a stationary observer, then vertical relative motions are produced by parts of the environment at different distances. For depth surfaces defined by vertical parallax motion, the two suggested explanations for the anisotropy lead to different predictions. If the anisotropy is due to a difference in the number or extent of the underlying horizontal/vertical spatial interactions, then the same pattern of anisotropy should be found for vertical and horizontal parallax motion. It should again be more difficult to perceive low frequency corrugations when they are oriented vertically, than when they are oriented horizontally. On the other hand, if the anisotropy is due to differences in the processing of shear and expansion transformations, then it should show the opposite pattern when vertical motion is used to specify the depth surfaces. This is because, for depth surfaces specified by vertical relative motion, a vertical corrugation is specified by a shear transformation while a horizontal corrugation is specified by an expansion/compression. A low frequency horizontal corrugation should, therefore, be more difficult to perceive than a low frequency vertical corrugation and this is the opposite pattern to that observed when the corrugations are specified by horizontal relative motion. Preliminary observations suggest that the latter prediction is correct. It was found that the direction of the anisotropy reversed when vertical parallax motion was used to specify corrugated depth surfaces. This finding suggests that the observed anisotropies for threshold measures, and for the Cornsweet illusion, are a result of the different patterns of velocity or disparity change over space, which are present for vertical and horizontal depth surfaces.

The presence of large simultaneous contrast effects in the depth domain has shown that spatial interactions are an important feature in the processing of both motion parallax and stereoscopic information. Further investigation of one of these contrast effects led to the discovery of anisotropies within the perception of depth surfaces.

Such anisotropies were reflected in both threshold and supra-threshold measures of sensitivity to depth modulations. These anisotropies indicate that the mechanisms which respond to depth change over space are likely to be asymmetric. It also seems likely that the extraction of depth change in a direction orthogonal to the direction of motion, or disparity, specifying the depth, is easier than the extraction of depth change in a parallel direction.

The experiments reported so far have pointed to the possible nature of the processing mechanisms within the separate parallax and stereoscopic systems. Since there seem to be many similarities in processing between the two systems it seemed likely that the two systems might influence each other at some stage of processing. The following chapter looks at the types of interaction that occur between depth information from motion parallax and that from stereoscopic cues and provides further evidence for the underlying structure of depth processing.

Chapter 8 Interactions between Motion Parallax and Stereoscopic Depth Processing

The phenomenal impression obtained on viewing a depth surface specified by motion parallax information is very similar to that obtained for a stereoscopic surface. In addition, as shown by the experiments reported in this thesis, the two systems share many empirical characteristics. The motion parallax and stereoscopic systems have so far been considered as separate, independent processing systems which extract depth information from different sources. That motion parallax can act effectively as a source of depth information independent of stereopsis and other depth cues, has been clearly demonstrated using the techniques described earlier. The fact that random dot stereograms can portray depth surfaces demonstrates that binocular disparity is also sufficent to specify depth in the absence of other information. In natural situations as well, it is important that the two systems can act independently. For example, when viewing at a large distance only parallax information is available, while stereopsis is present, without parallax, when the observer is stationary. However, in most everyday situations both sources are readily available. It is therefore of interest to ask whether the independence of the two processing systems is maintained throughout the visual system or, on the other hand, whether there are interactions between the two depth processing systems at some level, which allow depth information from the two sources to be combined. It had previously been difficult to look at the interactions between the two depth systems in a way which allowed both sources of depth information to be independently manipulated. The present chapter describes some experiments which used a modified version of the earlier experimental arrangement to investigate such interactions.

8.1 Method.

To allow both stereoscopic and parallax information to be provided in the same experimental situation, a modified experimental display was designed, as shown in Figure 8.1. It consisted of a stereoscopic viewing apparatus where random dot patterns on two oscilloscope screens were viewed independently by the two eyes, by means of mirrors. The two oscilloscopes were mounted on a platform which was suspended from a height of seven feet and which could swing from side to side across the observer's line of sight. The mirror arrangement allowed the oscilloscope screens to be visible throughout the extent of their lateral movement. When the platform was set in motion and the observer looked through the mirrors, the two patterns on the screens were fused and seen as a single pattern which moved from side to side. Either of the two random dot patterns could be blanked out to provide monocular rather than binocular information. The suspended platform was constrained to move through 15 cms. and the motion of the platform was monitored by a photocell. The photocell signal triggered a function generator which provided a sinusoidal signal which followed the position of the scope and oscillated with a temporal frequency of about 0.3 Hz.

To produce stereoscopic depth information, a disparity signal, produced using the Wavetek arbitrary waveform generator, was added to one of the two scopes while an identical signal with inverted amplitude was added to the other. This created horizontal disparities between

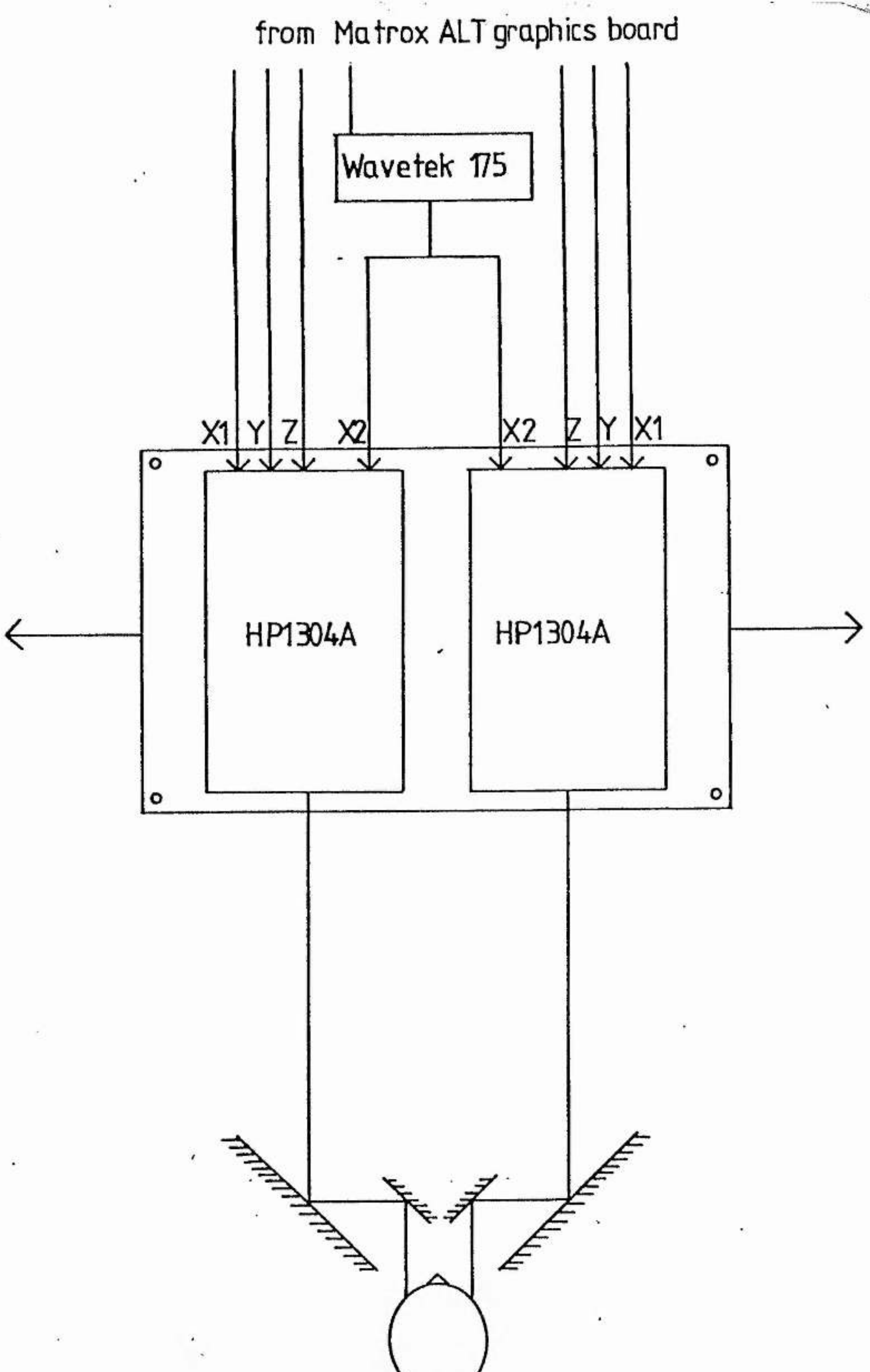


Figure 8.1.

The modified experimental display: Stereoscopic information was provided by disparities between the random dot patterns on the two oscilloscopes which were viewed independently through a fixed mirror arrangement. To provide parallax information patterns of relative motion were introduced into either or both of the patterns and the extent of relative movement was linked to the movement of the scopes which swung from side to side across the observers line of sight.

the random dot patterns on the two scopes so that when they were fused a depth surface was perceived, the shape of which was determined by the waveform of the disparity signal.

To produce parallax depth information, the signal triggered by the photocell was used to amplitude modulate the signal from the arbitrary waveform generator. The amplitude modulated signal could be added to either or both of the patterns to provide parallax information to either or both eyes. The parallax signal resulted in a continuous pattern of relative motion between different parts of the random dot pattern as the platform moved from side to side. The relative motion simulated the parallax information provided by a three-dimensional depth surface, where the shape of the surface was determined by the waveform of the parallax signal from the generator. When the observer looked through the mirrors, a single, solid, three-dimensional surface was seen to move to an fro across the line of sight, and the relative motion within the surface was not perceived. Since the observer remained stationary while viewing the depth surface, a passive parallax situation was simulated (see page 54).

By adding the disparity and parallax distortion signals to produce a composite distortion signal, both parallax and stereoscopic information could be provided at the same time. However, in most of the experiments described here, the two sources of depth information were used separately.

8.2 Preliminary Observations.

i) Binocular Parallax without Stereopsis

The modified experimental arrangement allowed monocular parallax depth information to be presented to either eye alone in the usual way. For example, when a sinusoidal parallax signal was added to one of the patterns, while the other screen was made blank, a corrugated depth surface was perceived as the platform moved from side to side. In the new arrangement, however, it was also possible to present parallax information to both eyes simultaneously, by adding the same distortion signal to the two random dot patterns, which were viewed independently by the two eyes. In this situation, when the two random dot patterns are identical, stereoscopic information is available in addition to the monocular parallax information specifying a corrugated depth surface. When the disparity between the two patterns is zero, the stereoscopic information specifies a flat depth surface. Observers reported that, when parallax information was presented binocularly with zero binocular disparity, the stimulus did appear as a corrugated depth surface moving from side to side, but some motion was also perceived within the depth surface. This motion was described as a shearing between different parts of the pattern or a twisting of the surface about an axis through the surface.

Alternatively, a more interesting situation arises when a different random dot pattern is presented to each eye. In this case, stereoscopic information is no longer available because the two patterns are rivalrous. Relative motion can, however, still be introduced to each pattern separately, thus providing parallax information to each eye which specifies a depth corrugation. It was found that, in this condition, a solid corrugated depth surface was easily perceived despite the surface texture having a shimmering appearance due to the binocular rivalry. The perceived depth of the surface appeared to be similar to that obtained in the normal situation of monocular parallax. It was therefore possible to produce a depth surface which was specified binocularly, in the absence of any stereoscopic information from binocular disparity.

ii) Stereopsis without parallax

When sinusoidal horizontal disparities are introduced between the two random dot patterns in the present display, a corrugated stereoscopic surface is perceived when the two patterns are fused. In the everyday environment, the stereoscopic information from three-dimensional surfaces is accompanied by parallax information when the surface moves relative to the observer. Therefore, if the two scopes are moved from side to side across the observers line of sight, and no parallax distortion signal is added to either pattern, then stereoscopic depth information is available in a situation where it would normally be accompanied by motion parallax. Observers were asked to describe the appearance of the display when the stereo information specified a corrugated depth surface, but there was no relative motion within the pattern as the scopes moved from side to side. They reported that a solid corrugated depth surface was perceived moving across the line of sight, but that this surface appeared to follow a concave path around the observer rather than a linear lateral path across the line of sight. The surface appeared to follow a path such that it always appeared to be facing the observer.

An analogous phenomena can be observed when viewing a random dot stereogram while moving the head laterally (Julesz, 1971). Here, the stereoscopic form appears to turn and follow the movement of the observer. In both these cases, the absence of appropriate parallax information results in the perceived movement of the stereoscopic figure. The phenomenal impression obtained, in fact represents the physical situation which the available information most closely approximates. The only situation in a natural three-dimensional environment where stereoscopic information is available about the structure of a moving object or surface, but where there is no relative motion between nearer and farther parts of the surface, is one where the depth surface moves in a circular path around the observer. The perceived situation, therefore, is in accordance with the appropriate physical situation.

The current stimulus display allowed stereo and parallax information to be provided together. It was therefore possible to look at what was perceived when the appropriate parallax information was gradually introduced as the stereo depth surface moved from side to side. It was found that, as the appropriate parallax information was added, the perceived path of the corrugated depth surface gradually changed. When there was no parallax information the surface appeared to move around the observer. As the amplitude of the parallax signal increased, the path became less concave until, when both the parallax and stereo signals specified a depth surface of the same amplitude, the corrugation appeared to move along a linear lateral path, orthogonal to the line of sight. That is, the path of the surface was perceived veridically. In this situation, then, the parallax information does not seem to provide additional depth information in itself, but stereoscopic and parallax information do interact to determine the perceived path of the depth surface.

iii) Parallax and stereopsis in conflict

The previous observation indicated that parallax and stereo information could interact at some level. It was therefore interesting to look at what was perceived when the two sources provided information specifying different depth surfaces, that is, the two sources conflicted. It might be assumed that depth information from the two sources could add in some quantitative way so that, for example, when a corrugated surface in one phase was specified by binocular disparity but a corrugated surface of the opposite phase was specified by motion parallax, then the depth information from the two sources would cancel out and no depth would be perceived. When such a situation was presented to observers it was found that no such quantitative cancellation of this kind occurred. Instead, a corrugated depth surface was perceived and the phase of the perceived corrugation was that specified by the binocular disparities. That is the perceived depth was determined by the stereoscopic information. However, as observers viewed the corrugation they reported that it appeared to rotate about a vertical axis in the centre of the surface, as well as moving from side to side. Therefore, the conflicting parallax information did not alter the depth percept given stereoscopically but was, in some sense, interpreted in the light of this depth structure to produce the perception of a rotating three-dimensional object. To summarise, when stereoscopic information is put into conflict with motion parallax, the perceived depth structure is that specified by disparity and the parallax information specifies the path of motion of the depth structure.

This observation, that parallax motion does not alter the perceived depth of a stereoscopically defined surface but does specify the motion path of the depth surface, sheds some light on some of the earlier studies of motion parallax where information from relative motion was contradicted by information from other depth sources. In cases where isolated points were used to provide parallax information, it was often ineffective in correcting the non-veridical information provided by other cues. If an object is misperceived at a certain distance then the addition of parallax information results in the object appearing to move with motion of the observer (Gogel and Tietz, 1973). In a series of experiments, Gogel has in fact used the extent of object motion concomitant with head motion to measure the perceived distance of objects under different conditions (Gogel and Newton, 1976; Gogel and Tietz, 1977; Gogel, 1979a; 1979b).

In summary, from these initial observations it seems that there is no quantitative interaction between depth information from stereopsis and that from motion parallax, although the two sources do interact in determining the final percept. Further experiments have shown, however, that both qualitative and quantitative interactions can occur between the stereo and parallax systems under certain circumstances, so that information from the two sources combines to determine the perceived depth of three-dimensional surfaces. These experiments have looked at aftereffects of depth following prolonged viewing of depth surfaces specified by parallax or stereoscopic information.

8.3 Biassing the perception of ambiguous depth surfaces.

Another method of looking at possible interactions between the motion parallax and stereoscopic systems arose out of the experiments on depth aftereffects which were described in chapter 4. In these experiments it was shown that prior inspection of a depth surface specified by either parallax or stereopsis strongly affected the subsequent perception of surfaces specified by the same depth cue. It seemed possible that, in addition to this negative aftereffect, adaptation to parallax or stereoscopic depth might also influence the subsequent perception of depth surfaces specified by the other depth cue. A similar approach was used by Harris (1980) to look at possible interactions between the depth cues of linear perspective and stereopsis.

Some initial observations suggested that this type of interaction was a possibility. Firstly, it was found that after viewing a corrugated depth surface specified stereoscopically, a flat test surface, which was presented monocularly, appeared to be corrugated with the opposite phase. That is, prolonged viewing of stereoscopic depth gave rise to a monocular negative aftereffect, as well as to a traditional binocular aftereffect. This observation had not been previously reported in the literature on stereo aftereffects, but it was easily observed with the modified experimental display when the random dot pattern to one eye was blanked out following inspection of a stereoscopic surface. It seemed likely that the presence of this monocular stereo aftereffect would affect the perception of parallax depth surfaces presented subsequent to stereoscopic adaptation.

Secondly, and conversely, it was also observed that after adaptation to a parallax depth surface which was presented monocularly, a negative depth aftereffect was observed when a flat test surface was presented to the unadapted eye. That is, there was transfer of adaptation between the two eyes. In addition, a small aftereffect following monocular viewing of a parallax surface, was also observed when a flat zero disparity test surface was presented. Therefore, prior inspection of a parallax surface gave rise to a binocular depth aftereffect. This suggested that adaptation to parallax depth might influence the perception of subsequently viewed stereoscopic surfaces. In order to examine these possible interactions in more detail, two experiments were carried out. These looked at whether it was possible to bias the perception of an ambiguous depth surface, which had two alternate depth interpretations, by prior inspection of an unambiguous depth surface specified by the other depth cue.

i) Biassing of ambiguous parallax depth

In the first experiment observers inspected a stereoscopic depth surface, which was sinusoidally corrugated in depth, for several seconds. After this inspection period, an ambiguous parallax test surface was briefly presented. The ambiguous test surface had two possible depth interpretations and could be perceived as a corrugated depth surface in either of two opposite phases. It was assumed that, if prior stereoscopic adaptation did affect the perception of parallax surfaces, then the perception of the ambiguous depth surface would be biassed in favour of one interpretation according to the phase of the adapting stereoscopic corrugation.

Using the apparatus shown in Figure 8.1 the stereoscopic adapting corrugation was produced by introducing horizontal disparities between the two random dot patterns on the display oscilloscopes. The corrugated adapting surface had a spatial frequency of 0.2 cycles per degree and a peak to trough disparity of 10 min arc.

The ambiguous parallax test surface was produced by introducing a pattern of relative velocities into one of the random dot patterns. The other pattern was blanked out for the duration of the test period. The pattern of relative velocities was produced by displacing each of the rows of the pattern by an amount which changed sinusoidally from the top to the bottom of the pattern. This is illustrated in Figure 8.2a where the arrows indicate the amount of displacement of each row during the test period and hence represent the relative velocity of each row. The duration of the test period was 2 secs during which time the dots moved in one direction. Both the observer and the swinging platform on which the scopes were mounted remained stationary throughout this experiment. Since the pattern of relative motion which occurred during the test period was not accompanied by any movement of the observer, or of the oscilloscopes, the perceived depth was ambiguous. When observers viewed the test stimulus without any prior adaptation, a corrugated depth surface was perceived and the surface appeared to rotate through a few degrees about a vertical axis through the centre of the surface. This observation was described in chapter 3 (page 62). The depth surface was ambiguous in that it could either be seen as a corrugated surface in one phase which rotated in one direction through a few degrees (Figure 8.2b), or as a corrugated

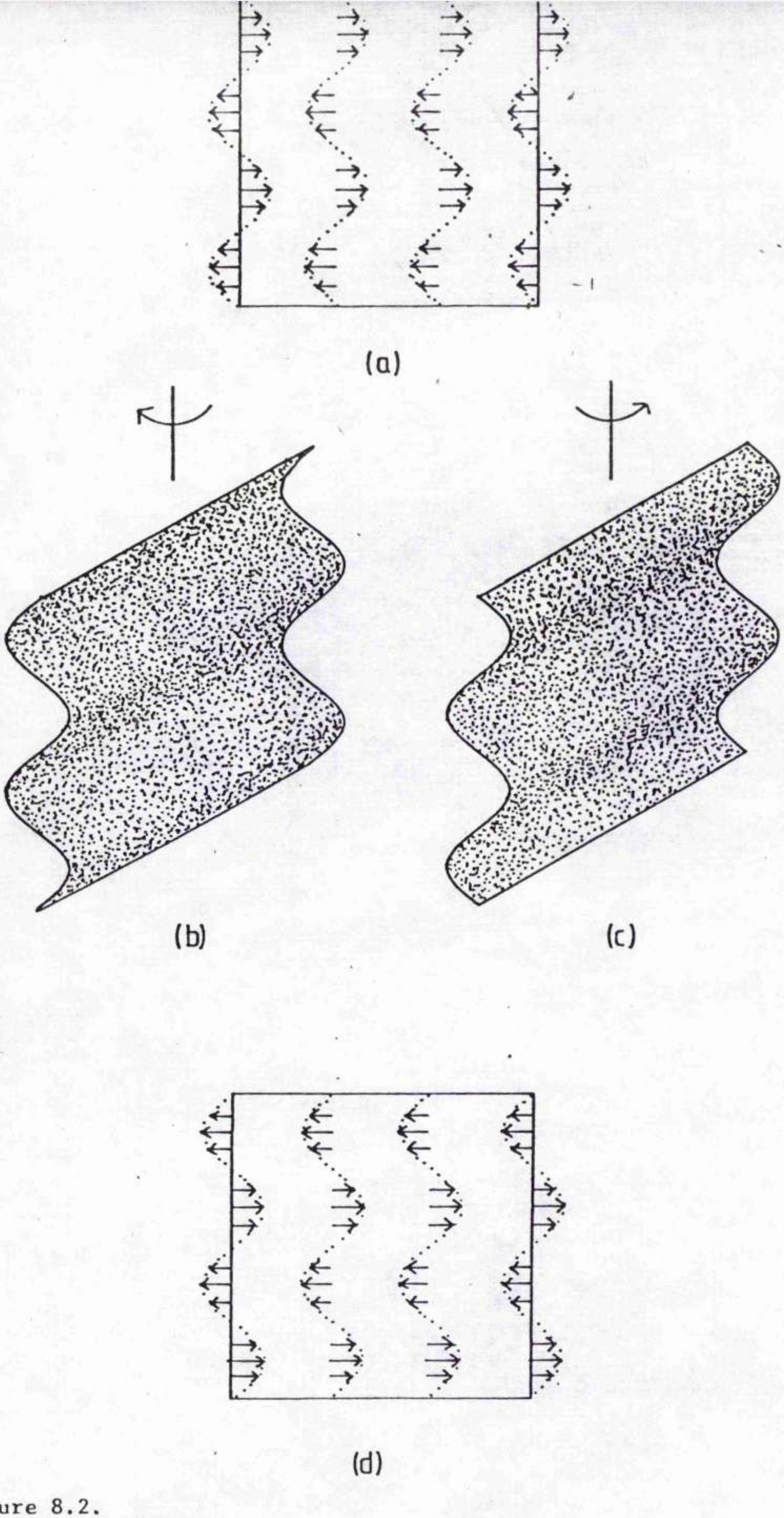


Figure 8.2.

An ambiguous parallax depth surface was produced by introducing the pattern of velocities shown in (a) into the random dot pattern.Both the observer and the scope remained stationary as each row of the pattern was displaced briefly as shown. The pattern was perceived either as a corrugated surface i one phase rotating anticlockwise (c) or in the other phase rotating clockwise (b). When the direction of relative velocities was reversed (d) the two possible phases were then associated with the opposite direction.

surface in the opposite phase which rotated through a few degrees in the opposite direction (Figure 8.2c). The two possible interpretations were generally perceived with roughly equal probability on different occasions. The ambiguity perceived in this situation is similar to that perceived in the Kinetic Depth Effect (Wallach and O'Connell, 1953), where each of two possible front/back depth relationships is linked to a particular direction of perceived rotation. This ambiguity was discussed in chapter 2.

By reversing the actual relative velocities present in the random dot pattern (Figure 8.2d), an ambiguous surface could be produced where a particular phase was now associated with the opposite direction of motion to that for the original pattern of velocities. This fact was exploited in the experiment to avoid response bias on the part of the observer. Stimuli with either the pattern of velocities in 8.2a or 8.2d were presented on different test trials. The observer was asked to report the perceived direction of rotation of the corrugated surface, rather than its perceived phase. In this way, if observers perceived both stimuli as having the same phase, the reported perceived direction of rotation was different in the two cases.

In the experimental condition, observers were presented with the stereoscopic adapting corrugation for ten seconds (Figure 8.3a). One of the random dot patterns was then blanked out and, randomly, either of the two patterns of velocities (8.2a or 8.2d) which specified the ambiguous test surface was presented for two seconds (Figure 8.3b). On half the trials the test surface was presented to the left eye and on the other half it was presented to the right eye. At the end of the test period, the observer was asked to report the perceived direction

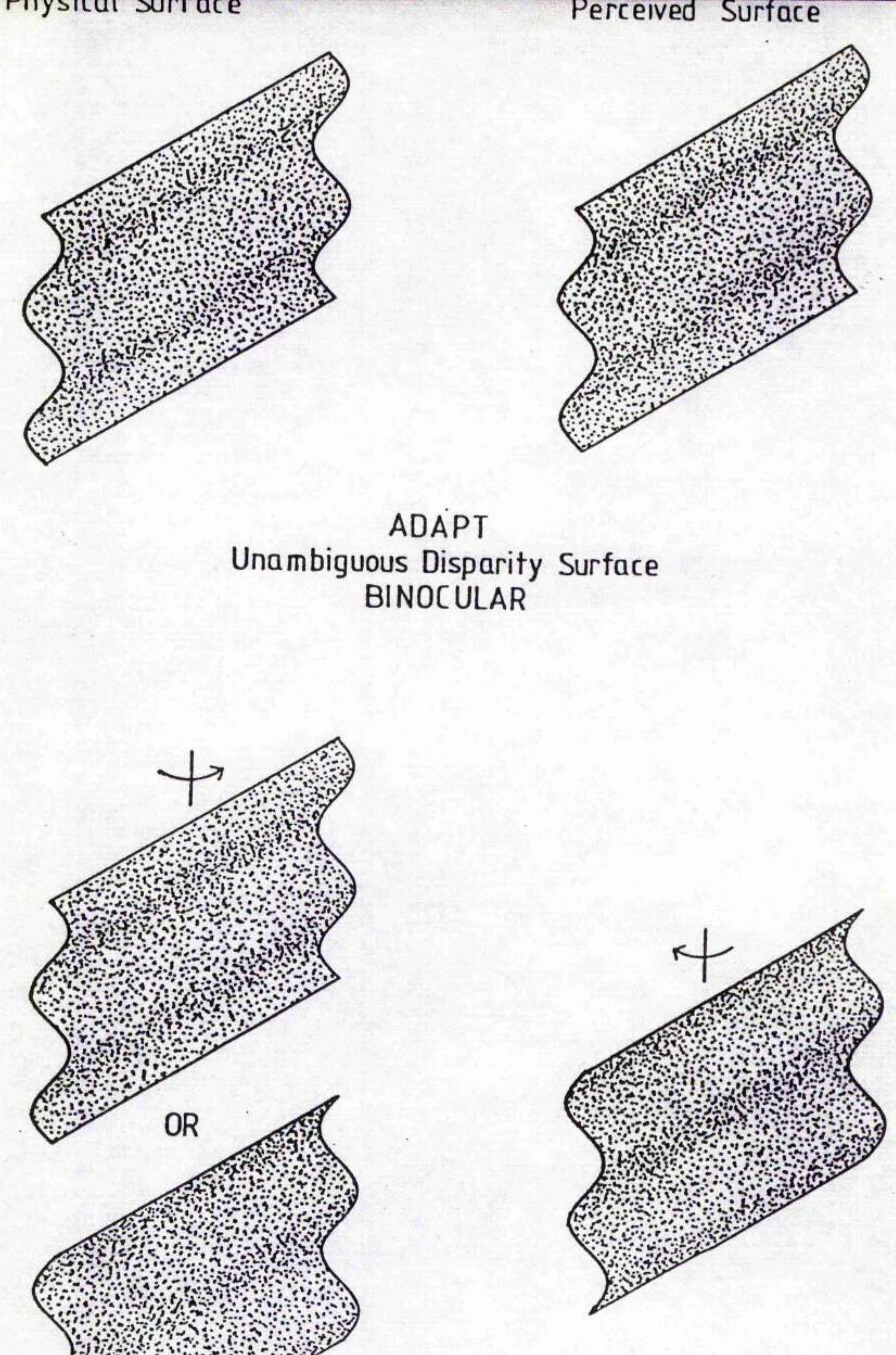


Figure 8.3.

Biassing of ambiguous parallax depth. The ambiguous parallax surface was briefly presented after viewing a binocular stereoscopic corrugation.

of rotation of the corrugated surface that was perceived during the test period. Cycles of adapt and test were carried out with the observer reporting the perceived direction of rotation after each test period. In a second block of trials the phase of the stereoscopic adapting corrugation was reversed and the same procedure was repeated.

A control condition was also carried out where a flat, zero disparity, stereoscopic surface was presented during the adapting period. Cycles of ten seconds of the flat stereo surface followed by 2 seconds of the ambiguous test surface were again presented and the observer reported the perceived direction of rotation of the depth surface presented during the test period. It was expected that, in this control condition, each of the two possible depth interpretations would be perceived, on average, 50% of the time while, in the experimental condition, the perception of the ambiguous corrugation would be biassed in favour of one phase rather than the other. Six subjects were given thirty trials in both the experimental and control conditions. Four of the observers were naive as to the purpose of the experiment.

The individual results obtained for the six subjects are shown in Figure 8.4a and the mean data in Figure 8.4b. The results show the same pattern for all subjects. In the control condition, after adapting to a flat stereoscopic surface, the ambiguous relative motion corrugation was perceived in each of the two possible phases about equally often, although some observers showed a slight bias towards perceiving one phase rather than other. In contrast, in the experimental condition, after inspection of a stereoscopic corrugation in one phase, the interpretation of the ambiguous relative motion

Perceived Test Phase

MEG (ADAPT)	A	B
Control	15	14
Phase A	0	29
Phase B	26	3

Perceived Test Phase

BJR (ADAPT)	A	B
Control	8	21
Phase A	0	29
Phase B	29	0

Perceived Test Phase

SW (ADAPT)	A	B
Control	19	11
Phase A	0	15
Phase B	14	1

Perceived Test Phase

TS (ADAPT)	A	B
Control	13	17
Phase A	0	15
Phase B	12	3

Perceived Test Phase

EC (ADAPT)	A	B
Control	17	13
Phase A	3	12
Phase B	13	2

Perceived Test Phase

AC (ADAPT)	A	B
Control	19	11
Phase A	1	14
Phase B	11	4

(a)

(Figure 8.4. - see over)

	Perceived Test Phase	
MEAN %	A	B
Control	51	49
Phase A	4	96
Phase B	87	13

(b)

Figure 8.4.

Biassing of ambiguous parallax depth:
(a) For each of the six observers the table shows the number of times that the ambiguous parallax surface was perceived in each of the two possible phases, following adaptation to a stereoscopic surface with zero disparity (control) or to a corrugated stereo surface in either of the two phases.
(b) The mean results are plotted for the six observers whose individual data were shown in (a). The data show the percentage number of trials in which the test surface was perceived in each of the two phases, for the three adaptation conditions.

corrugation was heavily biassed in favour of the opposite phase. The mean results show that in the control condition the ambiguous corrugation was perceived in one phase 49% of the time and in the other phase 51% of the time, while in the experimental condition the phase opposite to that of the adapting corrugation was perceived, on average, 92% of the time. Even for an observer such as BJR, where there was initially a strong bias towards reporting one phase in the absence of adaptation, the biassing effect of prior inspection of a stereoscopic surface was strong enough to completely overcome the initial bias.

In summary, the results clearly show that prior inspection of a binocular stereoscopic depth surface strongly biassed the subsequent interpretation of an ambiguous monocular depth surface where the depth was specified by relative motion. The biassing favoured the interpretation of the ambiguous depth corrugation which was opposite to that of the stereoscopic adapting corrugation.

ii) Biassing of ambiguous stereo depth.

The second experiment was converse to the first and looked at whether prior inspection of a motion parallax depth surface would bias the interpretation of an ambiguous stereoscopic surface.

As in the previous experiment, the adapting stimulus was a corrugated depth surface with a spatial frequency of 0.2 cycles per degree. In this case, however, the depth surface was specified by motion parallax information. Using the display described above, the observer viewed the pattern through the mirrors as the scopes on the platform moved from side to side across the line of sight. The pattern on one of the scopes was blanked out during the adapting period and relative parallax motion was introduced between the rows of dots in the other. The amount of relative displacement was amplitude modulated by the movement of the scope, hence simulating a passive parallax situation. When viewing this display observers saw a solid, stationary, unambiguous depth surface moving across their line of sight. The corrugated adapting surface was presented to either the left or right eye.

The test surface was an ambiguous stereoscopic depth surface which could be perceived as a corrugated surface in one of two opposite phases. To produce the surface, disparities were introduced between the two random dot patterns so that alternate matches between the elements of each pattern were possible. This technique was derived from the wallpaper illusion (Meyer, 1842) and has been used by Julesz (1971) to produce ambiguous random dot stereograms of various kinds. In these cases, a spatially repetitive pattern (in the simplest case black and white stripes) is used to generate a stereogram where each half contains the same pattern, but where the pattern is shifted by half its repetition distance in one half with respect to the other. This manipulation produces a situation where two equally possible matches can be made between the two halves of the stereogram and so the stimulus can be seen in either of two depth planes. The principle is illustrated for a striped pattern in Figure 8.5 (although in the present experiment the stereogram was made up of repetitive clusters of random dots rather than black and white bars). In addition, the spatial repetition rate was varied from the top to the bottom of the

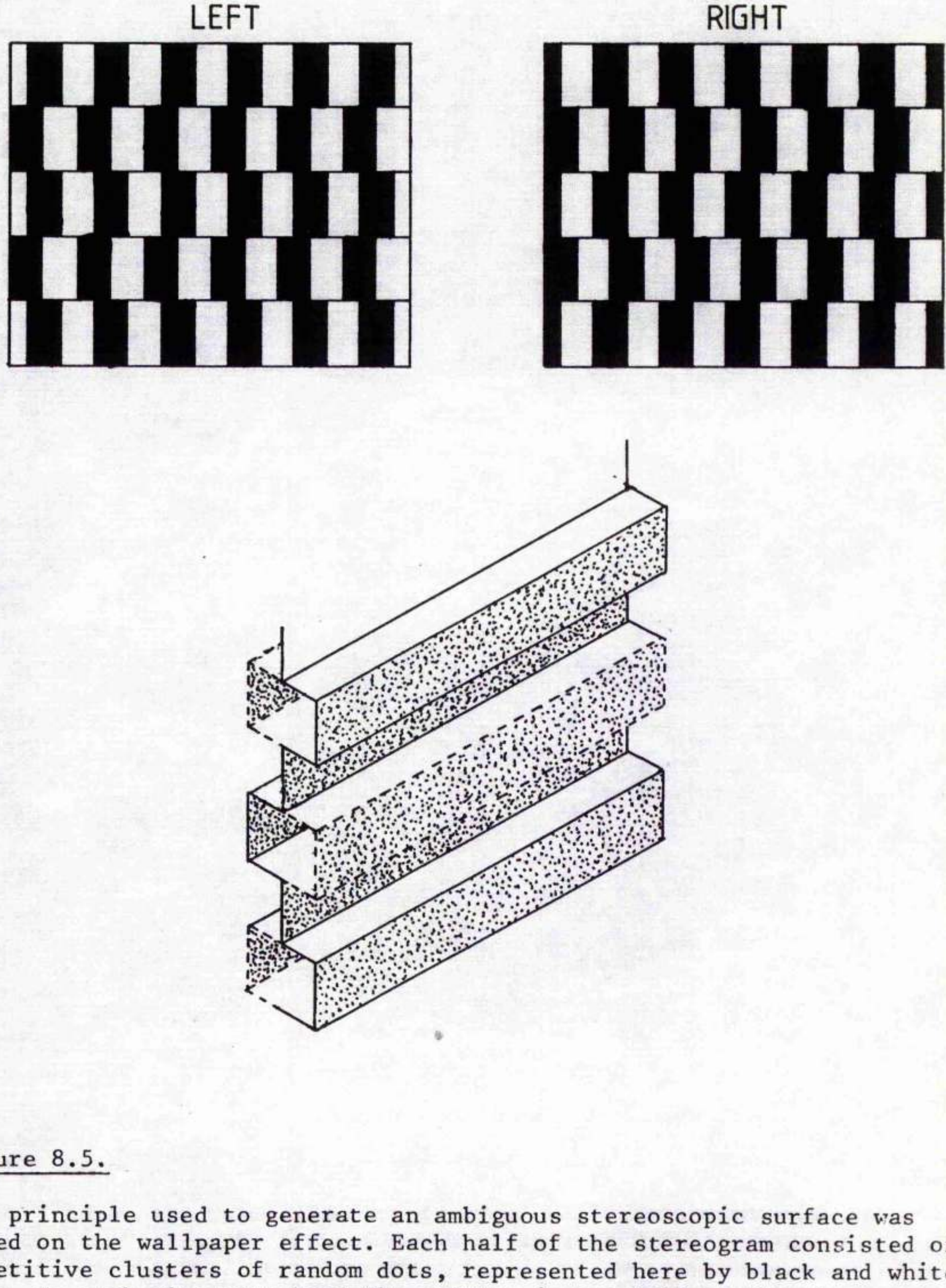


Figure 8.5.

The principle used to generate an ambiguous stereoscopic surface was based on the wallpaper effect. Each half of the stereogram consisted of repetitive clusters of random dots, represented here by black and white bars. In each alternate band the pattern in one half of the stereogram is shifted by half its repetition distance, with respect to the other half. Two equally possible matches are then possible between the two halves of the stereogram and an ambiguous depth surface is produced.

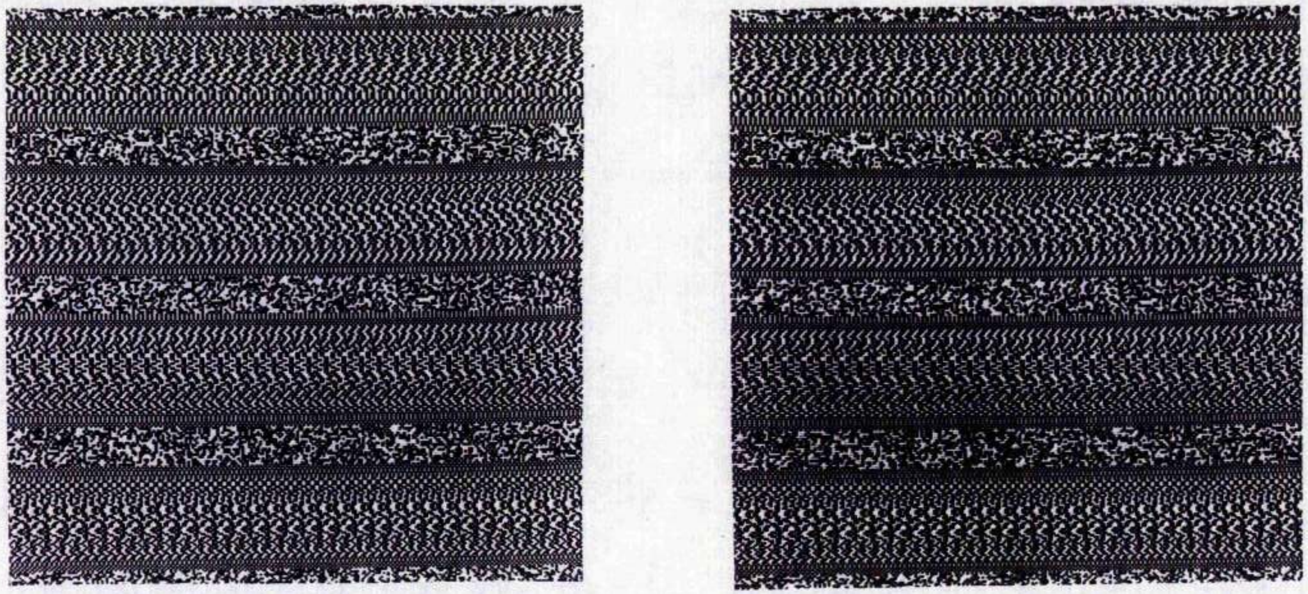


Figure 8.6.

The actual ambiguous stereogram used in the experiment is shown here. The spatial repetition rate of the dot pattern varied approximately sinusoidally from the top to the bottom of the pattern so that an ambiguous corrugated depth surface was produced.

pattern which made it possible to produce an approximation to an ambiguous sinusoidal depth corrugation. The stereogram actually used in the experiment is shown in Figure 8.6.

The procedure was the same as that used in the previous experiment and is illustrated in Figure 8.7. After an initial adapting period of two minutes, the unambiguous depth corrugation, specified by motion parallax information, was presented monocularly to either eye for 10 secs. The ambiguous stereo surface was then briefly presented binocularly, and the observer was asked to report the phase of the ambiguous corrugation with respect to the fixation point. Thirty trials of adapt-test sequences were presented in blocks of five with the phase of the adapting corrugation alternating between blocks. Randomly interspersed among these experimental trials were a series of catch trials in which the ambiguous stereoscopic surface was highly biassed in favour of the same phase as the adapting surface. This was done by introducing a continuous sinusoidal shift in one direction between the two halves of the ambiguous random dot stereogram. These catch trials were introduced to avoid any response bias or set on the part of the observer. As before, a control condition was carried out which was identical to the experimental condition except that the adapting surface contained no relative motion and appeared flat. This condition measured the relative frequency of perceiving the ambiguous corrugation in each of the two phases, in the absence of prior adaptation.

The individual results obtained for six observers are shown in Figure 8.8a and the mean data in Figure 8.8b. Again, the pattern of results was similar for all observers. However, the data for observer

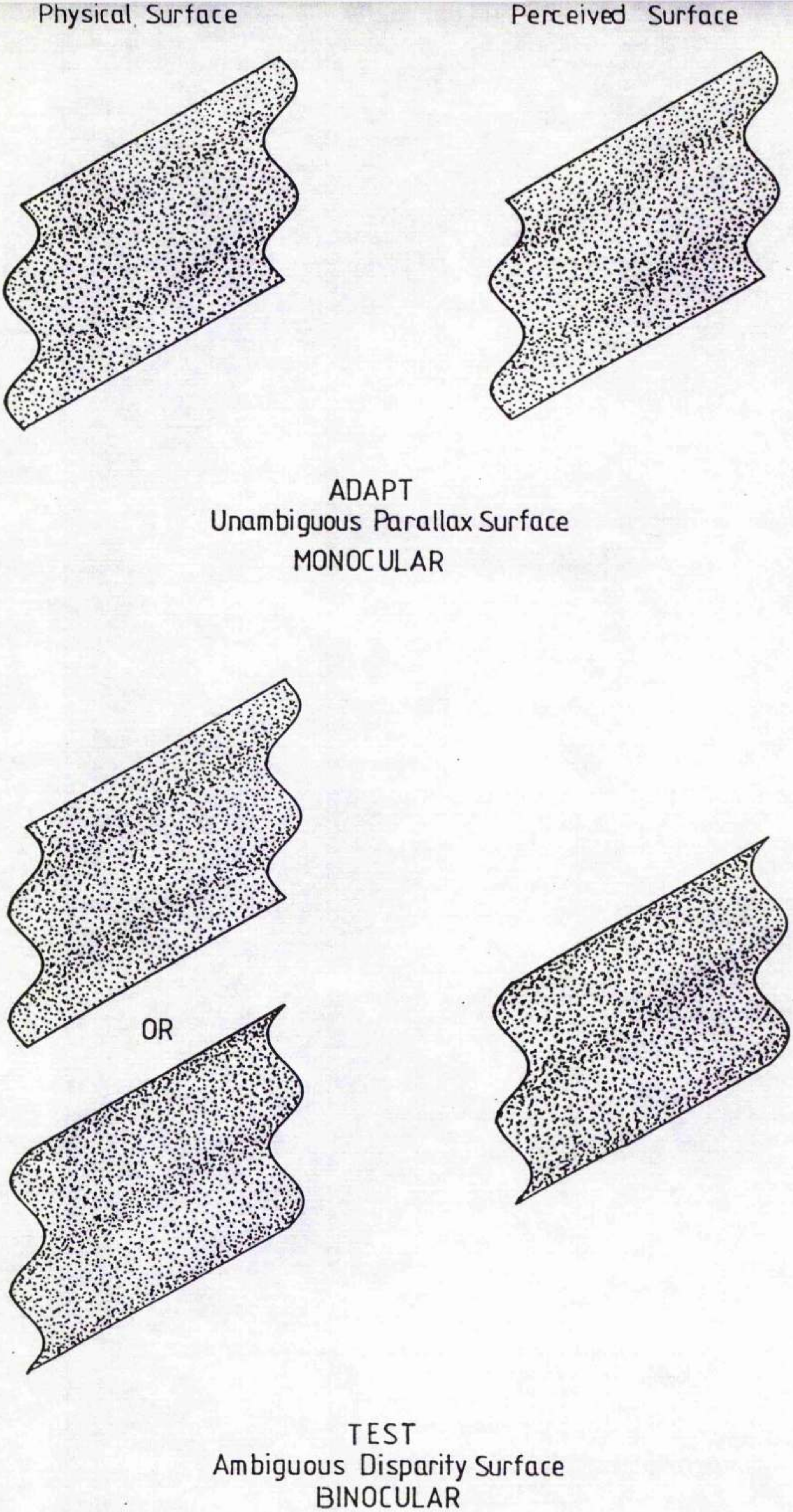


Figure 8.7.
Biassing of ambiguous stereoscopic depth. After viewing an unambiguous parallax depth surface the ambiguous stereogram was briefly presented and observers reported its perceived phase..

GQ are less clear and since this observer had reported difficulty with the task his data have been omitted from the mean data. Looking at the mean results, it can be seen that in the control condition, after inspection of a flat monocular surface containing no relative motion, the ambiguous stereogram was perceived in one phase 45% of the time and in the other 55% of the time. However in the experimental condition, after adapting to a parallax depth corrugation in one phase, the ambiguous stereogram was perceived in the opposite phase, on average, 90% of the time. It is notable that several observers had strong individual biases towards perceiving the ambiguous stereogram in one phase rather than the other, as shown in the control condition. However, even for these observers the biassing effects of adaptation to parallax depth were still strong.

iii) Discussion

The results of these two experiments have shown that, on the one hand, prior exposure to a stereoscopic depth corrugation can bias the subsequent interpretation of an ambiguous depth corrugation specified by relative motion, and, on the other, that adaptation to a depth corrugation specified by motion parallax can bias the interpretation of an ambiguous stereo corrugation. In both cases the effect of adaptation was to bias the perceived depth in favour of the depth corrugation with the opposite phase to the adapting corrugation (Rogers and Graham, 1983).

These findings show that information from the motion parallax and stereoscopic depth mechanisms does interact at some stage of visual

MEG	Perceived Test Phase A	Perceived Test Phase B
ADAPT Control	20	10
ADAPT Phase A	5	25
ADAPT Phase B	30	0

BJR	Perceived Test Phase A	Perceived Test Phase B
ADAPT Control	16	14
ADAPT Phase A	1	29
ADAPT Phase B	30	0

MB	Perceived Test Phase A	Perceived Test Phase B
ADAPT Control	3	12
ADAPT Phase A	2	13
ADAPT Phase B	14	1

TS	Perceived Test Phase A	Perceived Test Phase B
ADAPT Control	5	10
ADAPT Phase A	2	13
ADAPT Phase B	14	1

GQ	Perceived Test Phase A	Perceived Test Phase B
ADAPT Control	0	15
ADAPT Phase A	6	9
ADAPT Phase B	15	0

AC	Perceived Test Phase A	Perceived Test Phase B
ADAPT Control	8	7
ADAPT Phase A	3	12
ADAPT Phase B	12	3

(a)

(Figure 8.8. - see over)

MEAN %	Perceived Test Phase A	B
Control	45	55
Phase A	13	87
Phase B	94	6

(b)

Figure 8.8.

Biassing of ambiguous stereoscopic depth:
(a) For each of the six observers the table shows the number of times in which the test surface was perceived in each of the two possible phases following adaptation to either a zero disparity stereo surface (control) or a stereoscopic depth corrugation in either of the two phases.
(b) The mean data for the six observers shows the mean percentage number of trials in which the test surface was perceived in each of the two phases for the three adaptation conditions.

processing. This interaction may be some type of inhibitory linkage between the two systems or there might be some higher level depth process which receives inputs from the two systems. The biassing effects found here show the existence of essentially qualitative interactions between the two systems. It is possible that within a higher level depth mechanism, quantitative interactions between information from the two depth sources might also be possible. Although, as discussed above, quantitative interactions do not seem to occur when information from parallax and stereo directly conflict, it might be possible to demonstrate such interactions using the depth adaptation paradigm used in the present experiments. This possibility was investigated in the next experiment.

8.4 Quantitative Interactions between Depth Aftereffects

The strong depth aftereffects which follow prolonged viewing of stereoscopic or parallax depth surfaces were described in Chapter 4. The strength of these aftereffects was measured by nulling, or cancelling the perceived depth in the test surface with physical depth, until it appeared flat. In these original experiments the depth used to cancel the aftereffect was always specified by the same cue as that used to specify the depth in the adapting surface. The strong biassing effects found for ambiguous depth surfaces which have just been described, demonstrated that prior inspection of a depth surface specified by one depth cue biassed the subsequent interpretation of an ambiguous depth surface specified by the other cue. This finding suggested that it might also be possible to cancel or null negative depth aftereffects using depth information specified by the other depth cue. The experimental apparatus described at the beginning of this chapter allowed this possibility to be investigated.

i) Method

Throughout the experiment, the observer viewed the display through the stereoscopic mirror arrangement while the platform was swung from side to side across the line of sight through about 15cms. To provide stereoscopic depth information binocular disparities were introduced between the two random dot patterns. Monocular motion parallax depth information was provided by blanking out the pattern on one oscilloscope and introducing a pattern of velocities into the other. The relative motion was concomitant with the movement of the scope on the platform, thus specifying unambiguous parallax depth.

The experimental design contained the four conditions illustrated in Figure 8.9a. In each condition the procedure was the same. Observers were presented with a corrugated adapting surface of low spatial frequency for ten seconds and than a test surface was briefly presented for 2 seconds. During cycles of adapt and test, the observer was required to adjust the physical peak to trough depth of the test corrugation until the aftereffect was cancelled and the test surface appeared flat. In two of the experimental conditions the depth in the adapt and test surfaces were both specified by the same source of depth information, while in the other two conditions the adapt and test surfaces were specified by different sources. The same-cue conditions acted as a comparison for the cross-cue conditions. In one cross-cue condition, the observer was presented with a binocular

		TEST	
		Binocular Stereo	Monocular Parallax
ADAPT	Binocular Stereo	Adapt Stereo Test Stereo	Adapt Stereo Test Parallax
	Monocular Parallax	Adapt Parallax Test Stereo	Adapt Parallax Test Parallax

(a)

		TEST		
		Binocular Stereo	Monocular Parallax (left eye)	Monocular Parallax (right eye)
ADAPT	Binocular Stereo	✓	✓	✓
	Monocular Parallax (left eye)	✓	✓	–
	Monocular Parallax (right eye)	✓	–	✓

(b)

Figure 8.9.

Cancellation of depth aftereffect using depth specified by another cue:
(a) Thestrength of the depth aftereffect following adaptation to a corrugated depth surface was measured for the four conditions shown, using a nulling technique. In two conditions the aftereffect was cancelled using depth specified by the same cue as the adapting surface while in the other two conditions it was nulled using depth specified by the other cue.
(b) Seven conditions were actually measured in the experiment with monocular parallax information being presented to either the left or the right eye.

stereoscopic corrugation for several seconds. During the test periods a motion parallax corrugation was presented monocularly and the observer adjusted the overall amount of relative motion, and hence the peak to trough depth of the corrugation, until the surface appeared flat and the cross-cue aftereffect had been cancelled. In the other cross-cue condition, after viewing a motion parallax adapting surface, which was presented monocularly and where the depth was specified by relative motion, a binocular stereoscopic test surface was presented. During a sequence of adapt-test cycles the observer adjusted the amount of peak to trough disparity in the test surface until it appeared flat. In each case, the amount of peak to trough depth (specified by relative motion or disparity) that had to be added to the test surface to cancel the aftereffect was taken as a measure of the strength of the aftereffect. In all conditions the adapting surface was a sinusoidal corrugation of 0.1 cycles per degree and with a peak to trough disparity equivalent to 10 min arc.

Monocular parallax information could be presented to either the left or the right eye and both same-cue and cross-cue aftereffects were measured for both these cases. Aftereffects were, therefore, measured for a total of seven conditions as shown in Figure 8.9b. Several practice trials were carried out for each condition to familiarise observers with the task. When the observers were satisfied that they could perform the task consistently, four blocks of trials were carried out. In each block the strength of the aftereffect was measured for each of the seven conditions. Two observers took part in the experiment.

ii) Results

The results obtained for the two observers are shown in Figure 8.10. It was found that it was indeed possible to null or cancel the aftereffect produced following adaptation to either stereoscopic or motion parallax depth, using depth specified by the other cue. After inspection of a stereoscopic corrugation, a flat monocular surface appeared to be corrugated with the opposite phase and this perceived depth could be cancelled out by adding relative motion to the surface until it appeared flat. Conversely, after viewing a monocular parallax depth surface, a negative aftereffect was perceived using a binocular test surface and this could be nulled by introducing binocular disparities into the test surface.

From the data, the strength of the aftereffects measured using cross-cue nulling can be compared with those obtained when the same source of depth information was used to cancel the aftereffect. It can be seen that the cross-cue effects are somewhat smaller than those obtained for same-cue nulling. For example, for observer BJR, a peak to trough disparity equivalent to 3 min arc was needed for same-cue cancellation, that is, the strength of the same-cue effects were around 30 per cent. After adapting to stereo depth the monocular aftereffect was nulled by adding 2 min arc of motion parallax depth to the test surface, while, after adapting to parallax depth the binocular aftereffect was nulled by adding 1 min arc binocular disparity. Although these cross-cue effect were smaller, it should be noted that these are still sizeable effects, being above 10% of the depth in the adapting surface. This compares favourably with the strengths of aftereffects in other visual dimensions (Anstis, 1975). The data for

MEG		TEST	
	Stereo	Parallax Left	Parallax Right
ADAPT Stereo	5·2	1·7	1·7
ADAPT Parallax Left	1·8	2·1	–
ADAPT Parallax Right	1·6	–	2·2

BJR		TEST	
	Stereo	Parallax Left	Parallax Right
ADAPT Stereo	2·9	2·3	2·0
ADAPT Parallax Left	0·9	2·7	–
ADAPT Parallax Right	1·1	–	3·0

Figure 8.10.

The results in each of the seven experimental conditions shown in Figure 8.9b, are shown for the two observers. The data show the peak to trough equivalent disparity, or disparity, (in min. arc) that was needed to cancel the depth aftereffect in each condition. The adapting corrugation contained a peak to trough disparity equivalent to 10 min. arc in all conditions.

the other observer also show that smaller aftereffects occur for the cross-cue conditions. However, for this observer the strength of the same-cue aftereffect for stereo is rather large at about 50% and it is difficult to compare the pattern of results for the two observers.

To allow a comparison between the data for the two observers, the data can be expressed in relative terms, so that the strength of the cross-cue effects are expressed as a percentage of the same-cue effects. Figure 8.11 shows the pattern obtained when the data are calculated in this way. For this figure, the ratio of the parallax adapt/stereo test condition to the stereo adapt/stereo test condition (PaSt/SaSt) and the ratio of the stereo adapt/parallax test to the parallax adapt/parallax test condition (SaPt/PaPt), have been calculated. These ratios give a measure of the relative effectiveness of cross-cue nulling. If the strength of the same-cue effects is arbitrarily assigned a value of 100 per cent, then the effectiveness of cross-cue nulling can be expressed in percentage terms as illustrated in the histograms of Figure 8.11. From this figure, it can be seen that, for a monocular atereffect which was nulled using parallax information, prior viewing of a stereoscopic corrugation was about 75% as effective as prior viewing of a parallax corrugation. On the other hand, for producing a binocular aftereffect which was nulled stereoscopically, prior inspection of a parallax corrugation was about 33% as effective as prior viewing of a stereo corrugation. The pattern of results for the two observers are similar when the data are expressed in these terms.

iii) Discussion

Relative Effectiveness of Cross-cue Adaptation can be computed by the ratios

$$\frac{S_a P_t}{P_a P_t} = \frac{\text{Stereo-Adapt Parallax-Test}}{\text{Parallax-Adapt Parallax-Test}}$$

$$\frac{P_a S_t}{S_a S_t} = \frac{\text{Parallax-Adapt Stereo-Test}}{\text{Stereo-Adapt Stereo-Test}}$$

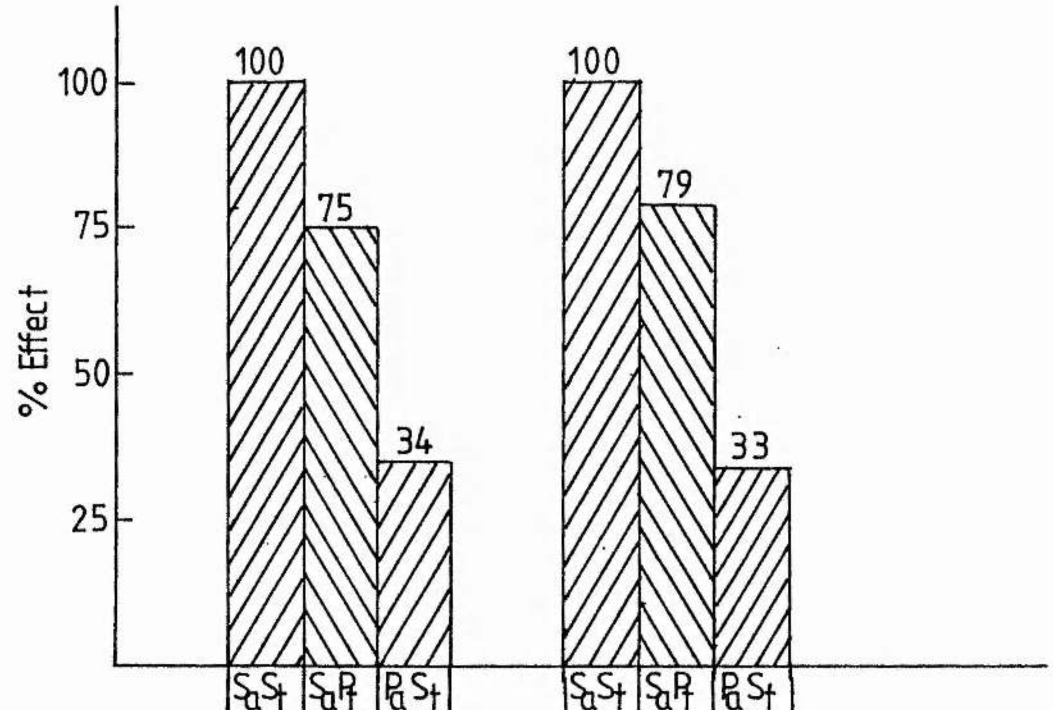


Figure 8.11.

The relative effectiveness of cross-cue adaptation was determined by computing the ratios S_aP_t/P_aP_t and P_aS_t/S_aS_t from the data shown in Figure 8.10. The percentage relative effectiveness can be illustrated as shown below, where the strength of the same cue effects (S_aS_t and P_aP_t) have been arbitrarily assigned a strength of 100 per cent.

The results demonstrate that negative depth aftereffects which arise after viewing a parallax or stereoscopic surface, can be cancelled using depth information from the other source (Graham and Rogers, 1982b). This indicates that quantitative interactions can occur between depth aftereffects in one depth system and depth from the other system. The cross-cue depth aftereffects found in the last experiment could also be responsible for the qualitative biassing effects described previously, since the presence of a negative aftereffect would be likely to bias the ambiguous perception in favour of the same phase as the aftereffect. It is important to note that both the qualitative and quantitative interaction effects described in this chapter, demonstrate not only that depth information from motion parallax and from stereopsis can interact but also that interactions can occur between binocular and monocular depth processes.

The quantitative interactions obtained with depth aftereffects are very different to the interactions described earlier which occur when stereo and parallax information are put directly into conflict. Here the interaction seems to be characterised by a "best fit" calculation, where the final perception is close to that of the real situation most nearly simulated by the information presented. No direct cancellation of depth from one source, by depth from the other, occurs in this situation. Although stereo and parallax normally act together as sources of depth information, when they conflict, the resultant depth percept is based on stereoscopic information. In some sense, the relative motion information is reinterpreted in light of the stereo information. It is therefore necessary to assume that the binocular stereo system can affect the motion parallax system at a stage where depth from relative motion is being computed. It is at first sight possible that the quantitative interactions between stereo aftereffects and parallax depth might also occur via this route. However, the stereoscopic aftereffect does not result in the reinterpretation of parallax information, which only occurs when stereoscopic information is directly available. Since the stereo aftereffect presumably reflects residual activity within the stereo system following adaptation, it is not clear why it should act differently from direct stereoscopic information. It seems more likely that the quantitative interactions between the two depth systems occur at a different level from that where direct stereo information influences the interpretation of parallax information.

A basic simple model of stereo-parallax interactions would therefore contain two levels where information from the one depth source could influence the other. Such a model is illustrated in Figure 8.12. The stereoscopic system is assumed to affect the parallax system at an early stage to allow the relative motion to be interpreted in light of information from binocular disparity. At this level the interaction is assumed not to be of a quantitative nature. In addition, information from the binocular stereoscopic and monocular parallax depth systems are assumed to combine together quantitatively at a higher level.

From the observations of successive and simultaneous contrast effects described in earlier chapters, it was suggested that aftereffects arise from the adaptation of depth processing units within the stereo and parallax systems which process the change in depth over local areas of space. In the present model, it is assumed that adaptation affects such mechanisms within the individual depth systems. It is however also possible that there are also adaptable mechanisms at the higher level where depth information is combined. This possibility seems at least plausible by the following argument. The finding that the stereo aftereffect does not lead to a reinterpretation of the parallax information and therefore acts differently from direct stereoscopic information, indicates that the route whereby stereo information influences the parallax system at an early stage of processing is inoperative in the case of the aftereffect. This may be because there is no binocular input in the test period when parallax is used to null the aftereffect. If it is assumed that the binocular system is not monitored at all when there is a monocular input, then it is necessary to suppose that adaptation to stereoscopic depth adapts units at the level of depth combination as well as within the stereo system. Otherwise no monocular aftereffect would be observed following stereoscopic adaptation and no cross-cue nulling could occur. The alternative possibilty is that activity within the stereo system is not ignored during monocular input and so, following adaptation, it can affect depth combination even though it does not directly influence parallax processing. It is, however, difficult to see why this should be the case.

Using the simple model shown in Figure 8.12 and assuming that in the absence of binocular input any activity within the stereo system is ignored, the observed stereo/parallax interactions can be accounted for in the following way. When a depth aftereffect is nulled using depth from the same source, then units are adapted within both the individual depth systems and at the higher level of depth combination. The resultant aftereffect is due to adaptation at both levels. However,

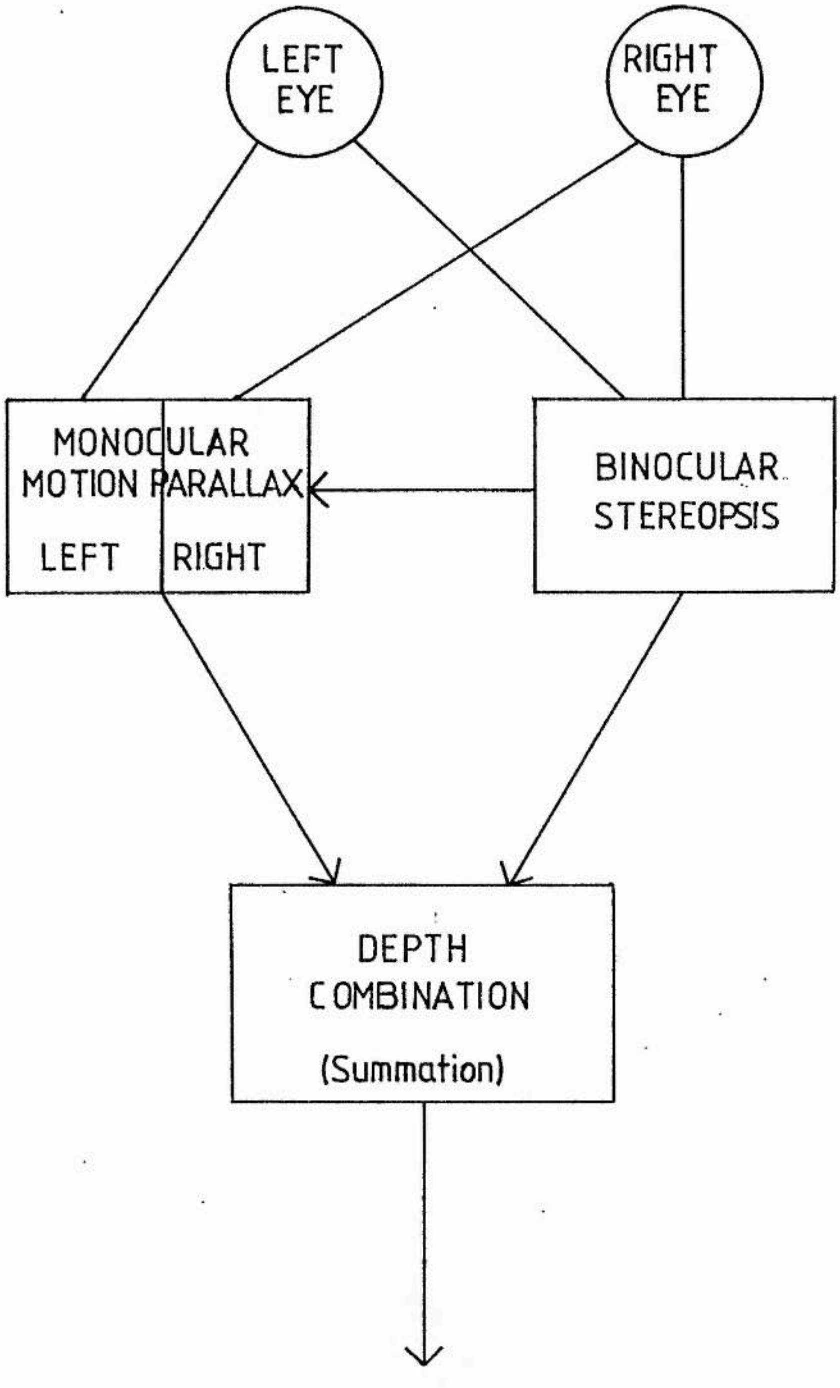


Figure 8.12.

A simple model of stereo-parallax interactions based on the interaction effects described in this chapter. The stereo and parallax depth systems interact at least at two levels. The stereo system affects the parallax system qualitatively at an early stage where the relative motion information is interpreted in light of information from binocular disparity. In addition, information from the two systems combines together quantitatively at a higher level.

when the aftereffect is nulled using depth from the <u>other</u> source, only the adapted units at the higher level, where depth information from the two sources is combined, will affect the percept. Hence, as observed in the last experiment, cross-cue aftereffects would be expected to be smaller than same-cue effects. Alternatively, it may be the case that the activity within the stereo system is not totally ignored during monocular input, but that the stereo input to the parallax system becomes inoperative for some other reason. In this case it would not be necessary to postulate adaptable units at the level of depth combination. A quantitative interaction at this level, between the activity in the stimulated channel and the residual activity in the adapted system, would then be sufficient to explain the cross-cue aftereffects.

In conclusion, the experiments reported in this chapter which describe various interaction effects between the motion parallax and stereoscopic depth processing systems, have demonstrated that interaction effects of two types are observed and the data are compatible with a model which assumes that depth information from the two sources is combined in a quantitative way at a higher level. It is possible that adaptable depth processing units exist at this level as well as within the separate parallax and stereo processing systems.

Chapter 9 The Processing of Depth from Motion Parallax -Summary and Conclusions

The first part of this thesis provided a theoretical and historical background to the research that had been carried out on the perception of depth and distance from motion parallax information. It was pointed out that although parallax had been recognised as an important source of depth information, at least since the time of Helmholtz, there had been relatively little empirical investigation of the characteristics of motion parallax processing. More recently there had been an increased emphasis on dynamic sources of information, following the work of JJ Gibson (1950; 1966). This had generated a renewed interest in the depth cue of motion parallax, which is one example of the motion perspective, or optic flow, which accompanies self-movement in the environment. However, the empirical studies which arose from this approach failed to provide clear evidence that motion parallax could act as an effective cue to depth and distance.

Arising out of the interest in the general properties of motion perspective, or optic flow, several mathematical analyses have been developed which specify the nature of the optic flow accompanying observer motion and the potential information available to a moving perceiver (Gibson et al., 1955; Nakayama and Loomis, 1974). In line with the increasing influence of computational approaches to visual perception, these analyses have recently been developed into computational models of optic flow processing. Several models are now available which describe the information available to the perceiver and show how the relevant information could, in principle, be computed (Koenderink and ven Doorn, 1976; Longuet-Higgins and Prazdny, 1980).

Moreover working computer algorithms have been successfully implemented in some cases. The development of computational models has provided a rigorous demonstration of the potential richness of the information from optic flow. This information can be used, on the one hand, to determine the parameters of a perceiver's own motion in the environment, and on the other, to determine the three-dimensional layout and structure of objects in that environment.

Despite the theoretical analyses of optic flow which demonstrate its potential as a powerful source of depth information, it was pointed out that empirical studies, which tried to determine whether such information was actually used by perceivers, had only produced equivocal evidence. Recent work, which has found more positive results, has mainly been concerned with how information from optic flow can be used to control locomotion in the environment rather than on how the three-dimensional structure of that environment might be perceived (Lee, 1980). The major part of this thesis was therefore concerned with the empirical study of motion parallax as a depth cue. In addition, this study complements the theoretical models which have recently been developed.

9.1 Summary of experimental results.

i) Motion parallax as an effective cue

The development of a random dot technique (described in chapter 3), allowed the parallax information provided by three-dimensional surfaces of arbitrary shapes to be simulated (Rogers and Graham, 1979). By using this technique, parallax information was provided in isolation from all other sources of depth information, yet the stimulus was rich enough and flexible enough for a detailed investigation of the parameters of the parallax processing system.

In the stimulus display, the observer viewed a two-dimensional random dot pattern while moving from side to side on a chinrest. The rows of dots within the pattern moved relatively to each other and the extent of this relative movement was determined by the movement of the observer from side to side. The pattern of relative movement simulated that which would have been provided by a real three-dimensional surface as the observer moved laterally while viewing that surface. Alternatively, in the passive parallax display, the observer remained stationary and the oscilloscope moved laterally across the line of sight. In this case the relative movement within the pattern was dependent on the lateral movement of the scope and the situation simulated that of a three-dimensional object translating across the line of sight. When observers viewed the transforming two-dimensional pattern a solid three-dimensional surface translating across the line of sight, was in fact perceived. The phenomenal impression of the perceived surface was reported to be similar to that obtained when viewing a random dot stereogram, where the depth is specified by binocular disparities. The depth in the perceived surface was well-defined and stable. The physical relative motion within the dot pattern was not perceived. Simulated surfaces of different shapes could readily be distinguished and moreover, the front-back depth relationships within the surface were always perceived correctly. The depth effect was not ambiguous as found in some earlier studies (and also in the Kinetic Depth Effect), where depth reversals have been found to occur. This lack of ambiguity depended on the link between the relative motion within the pattern and the lateral movement of the observer in the active parallax situation, or the lateral movement of the oscilloscope in the passive parallax situation.

It was also possible to match the depth perceived within a parallax depth surface with that in a stereoscopic surface of the same shape. Using this method it was found that the perceived depth in the parallax surface was related monotonically to the amplitude of the relative movement that was present (for a given extent of head movement) in the random dot pattern.

ii) Sensitivity to motion parallax information

As an initial characterisation of the parallax processing system, the sensitivity of the system to small depth modulations was measured as a function of the area over which the modulation occurred, i.e. the spatial frequency of the depth modulation (Rogers and Graham, 1982). It was found that the visual system was very sensitive to small relative displacements between parts of the random dot pattern. At maximum sensitivity, a peak to trough relative displacement of only 6 sec arc for each cm of head movement was required to perceive a depth corrugation where the peak and the trough of the corrugation were 2-4 degrees of visual angle apart. This sensitivity corresponds to being able to detect a depth corrugation where the difference in depth between the peak and the trough of the corrugation is only 1mm, from a viewing distance of 57cms. Motion parallax can therefore be used to pick up small depth changes within three-dimensional surfaces and so provide detailed information about their structure.

The range over which this degree of sensitivity to parallax information occurred was, however, limited. There was an optimal range of spatial frequencies (from about 0.2 to 0.4 cycles per degree) for detecting sinusoidal depth corrugations. For corrugated depth surfaces with a spatial frequency outside this optimal range, sensitivity declined substantially. The optimal spatial frequency for detecting depth modulation is very low compared with that measured for detecting luminance modulation over space. This suggests that the visual system is tuned to respond well to luminance profiles which change rapidly over space, but responds best to relatively gradual changes in depth.

Sensitivity functions were also measured for corrugated depth surfaces where the depth was specified stereoscopically rather than by relative motion. There was a very close similarity between the sensitivity functions measured for depth surfaces specified by the two different cues. For stereo surfaces, peak sensitivity also occurred between 0.2 and 0.4 cycles per degree and sensitivity decreased above and below this range. In terms of the maximimum sensitivity to depth modulations, stereo thresholds tended to be slightly lower than parallax thresholds, up to about a factor of two for some observers. The thresholds obtained for detecting stereo depth modulation compared well with those found in previous studies and corresponded to being able to perceive a depth corrugation with a peak to trough depth difference of only 20 sec arc (or about 0.5mm at a distance of 57cms).

The striking feature of the sensitivity data was the close similarity between the functions for stereoscopic and parallax depth. The optimal area for detecting depth change was the same whether the depth was specified by disparities or by relative movement. Since the task facing the visual system is functionally similar for stereoscopic and parallax depth, the observed empirical similarity may reflect this functional similarity. It is possible, therefore, that both depth processing mechanisms share similar properties which give rise to the observed functions.

iii) Depth aftereffects

To further investigate the nature of the mechanisms involved in processing depth information, supra-threshold contrast effects in the depth domain were measured (Graham and Rogers, 1982a). A striking example occurred after prolonged viewing of a corrugated depth surface. A subsequently viewed, physically flat test surface appeared to be corrugated in depth with the opposite phase to that of the inspection surface. This negative depth aftereffect was found to occur for depth surfaces specified both by stereoscopic information and by motion parallax. A nulling technique was used to determine the strength of the aftereffect. The amount of physical depth corrugation that had to be added in to the test surface to cancel the perceived aftereffect was measured. At the null point the apparent corrugation of the aftereffect was cancelled and the surface appeared to be flat. The depth aftereffects were found to be very large reaching a strength of 70 per cent, that is, 70% of the depth in the adapting corrugation had to be added in to the test surface to cancel the aftereffect.

A depth aftereffect following inspection of motion parallax depth had not been previously reported and, it was argued that, the presence of such an aftereffect demonstrated the existence of adaptive mechanisms within the visual system, which are sensitive to relative motion. It was also argued that the site of adaptation must be beyond the site of basic movement processing at a level where the motion information has been disambiguated. It was suggested that the best explanation of the negative aftereffect was that it was due to the adaptation of mechanisms which extracted the change in depth over space rather than the depth at individual points. The similarity between aftereffects following inspection of stereoscopic surface and those following inspection of parallax surfaces, suggested that stereo aftereffects might also arise from the adaptation of mechanisms designed to detect relative disparity, or change in disparity over space. This is in contrast to the explanation generally advanced to explain stereoscopic aftereffects, which attibutes them to the adaptation of mechanisms which extract the disparities of individual points in the image.

The negative depth aftereffects obtained after viewing parallax or stereoscopic surfaces were phase-specific since they depended on steady fixation, so that each area of the retina was stimulated by the same depth value throughout the adaptation period. It had been reported that, for stereoscopic surfaces, a phase-independent threshold elevation effect occurred, where the threshold for detecting a depth corrugation was elevated following adaptation with free fixation (Schumer and Ganz, 1979). However, the experiments reported here failed to find any evidence for phase-independent threshold elevation in the parallax domain, using the present methods and stimuli. This suggests that the adaptive mechanisms operate over fixed retinal areas and are not organised into phase-independent channels.

iv) Simultaneous depth contrast

The nature of the spatial characteristics of the mechanisms underlying depth processing was further elucidated by looking at simultaneous depth contrast effects, where the perceived depth of any particular part of a surface was found to depend on the depth characteristics of the surrounding area. Analogous depth contrast effects were found for surfaces specified by parallax depth information and for stereoscopic surfaces (Graham and Rogers, 1982a). Several examples of simultaneous depth contrast were discussed. A strong example was found when observing a depth surface which contained a centre vertical bar surrounded by an inclined plane. On viewing this surface, the centre bar appeared to be sloping in depth and the direction of the slope was opposite to the direction of the slope of the inducing surround. This effect was measured using a nulling technique where the perceived slope of the centre bar was cancelled, by adding in a physical slope in the opposite direction, until it appeared to lie in the vertical plane. The strength of the contrast effect was found to be around 40%, that is, a slope equivalent to 40% of the slope of the surround had to be added in to cancel the contrast effect and make the centre bar appear vertical. The contrast effect had a similar strength when the surface was specified stereoscopically.

v) Anisotropies in depth processing

One type of depth contrast effect was found to be of particular interest. This was based on the well-known Craik-O'Brien-Cornseet illusion which has been studied in the luminance domain. In the depth domain the Cornsweet illusion can be observed when two areas at equal depths are separated by a spur-shaped change in depth. The two areas then appear to be at different distances from the observer. It was found that there was a large anisotropy in the extent of this illusory depth difference. When observers viewed a Cornsweet-shaped surface where the centre edge was oriented horizontally there was little or no illusion, but when they viewed a Cornsweet-shaped surface with the edge oriented vertically there was a large illusion, with the two flanks of the surface appearing to lie at very different depths.

Since the Cornsweet illusion is thought to arise from sensitivity differences to the different component rates of change in the surface, it was predicted that there should also be an anisotropy in the sensitivity functions for detecting horizontally and vertically oriented sinusoidal corrugations. It was found that sensitivity to vertically oriented corrugations was much poorer at low spatial frequencies than sensitivity to horizontally oriented corrugations. At higher spatial frequencies there was either no difference in horizontal-vertical sensitivity, or sensitivity was slightly better for vertically oriented corrugations. These differences in horizontal-vertical sensitivity were also present for depth surfaces which were considerably above threshold. A matching task was used where vertically oriented depth corrugations were matched in peak to trough depth with horizontally oriented corrugations. It was found that, at low spatial corrugation frequencies, when the peak to trough depth was perceived to be equal, the physical depth of the vertical corrugation had to be much larger than the depth of the horizontal corrugation.

Since the anisotropy was present for depth surfaces specified by motion parallax as well as for stereoscopic surfaces, it seems less likely to be due to the inherent anisotropy of the stereoscopic system (which extracts only horizontal disparities). It was suggested that the anisotropy might reflect asymmetries in the spatial organisation of depth processing mechanisms within both the stereoscopic and parallax depth systems. This asymmetry might be related to the orientation of the underlying receptive fields so that, for example, units would have smaller inhibitory regions in a vertical direction than a horizontal direction. Alternatively, it was argued that the anisotropy could be due to differences in the patterning of relative velocities or disparities which specify vertical, as opposed to, horizontal depth surfaces. In particular, the processing of vertical depth surfaces requires picking-up expansion and compression movements over local areas of the visual field. To extract this information, the changes of velocity in a direction parallel to the direction of the velocity itself must be computed. For horizontal surfaces, on the other hand, shear transformations between neighbouring areas must be processed. These require the extraction of changes in velocity in a direction orthogonal to the direction of the velocity itself.

vi) Interactions between parallax and stereopsis

The phenomenal impression of a depth surface specified by motion parallax information is very similar to that perceived on viewing a stereoscopic surface. As noted above, this similarity was also reflected throughout the experimental data. In the main body of experiments reported here, the two depth systems were treated independently and considered as separate processing systems which extract depth information from different sources. It was suggested, however, that at some stage within the visual system the two systems might interact in some way and experiments were designed to investigate these possible interactions.

The motion parallax and stereoscopic depth processing systems were found to interact in two different ways. When both motion parallax and stereopsis were present in the same stimulus, the perceived depth relationships within the depth surface were in accordance with the stereoscopic information. However, the available parallax information did influence the perceived path of the depth surface with respect to the observer. For example, when parallax and stereo information were put directly into conflict, such that one specified a depth corrugation in one phase and the other specified a depth corrugation in the opposite phase, the two sources of depth information did not cancel each other. The stimulus was perceived as a depth corrugation with the phase specified by the stereoscopic information and the surface was perceived to rotate about the observer. These findings can be characterised by saying that the visual system seems to use the stereoscopic information to specify the depth structure present, and then the relative motion information is interpreted in light of this depth structure to determine the path which would provide the "best fit" for the available patterns of relative motion.

A second type of interaction was also found to occur between the two depth systems. As mentioned above, prolonged viewing of either a parallax or a stereoscopic depth surface had been found to produce large negative aftereffects when a flat test surface was subsequently viewed. It was found that this negative depth aftereffect could bias the interpretation of an ambiguous depth surface, presented after adaptation, in favour of the phase <u>opposite</u> to that of the adapting surface. This was true when the ambiguous depth surface was specified by a different depth cue to that which specified the adapting surface. Prior adaptation to a stereoscopic surface biassed the subsequent interpretation of an ambiguous parallax depth surface and, conversely, prior viewing of a motion parallax surface biassed the subsequent interpretation of an ambiguous stereoscopic surface. In addition, it was found that after viewing a stereo surface, the subsequent monocular aftereffect could be nulled with depth specified by motion parallax and, conversely, after adapting to a monocular parallax surface there was a binocular depth aftereffect which could be nulled using binocular disparities. Although the strengths of these cross-cue adaptation effects were weaker than the same cue effects described before, they were still substantial.

Overall, the experimental data show that motion parallax is an effective and accurate source of depth information which shares many similarities with stereopsis. Sensitivity to parallax information can be high and is similar to that for binocular disparity. The large successive and simultaneous contrast effects found for both systems suggest that depth processing involves extended spatial interactions and that information about depth change over space is an important aspect of processing. Furthermore, the processing of depth change seems to show some interesting anisotropies. Finally, the motion parallax and stereoscopic depth systems seem to interact in different ways and information from the two sources may come together at some level within the visual system.

9.2 Implications for the nature of parallax processing.

The experiments described in this thesis, have demonstrated that motion parallax information can be effectively used by the human perceiver. What can be said about the processing underlying this ability? Firstly, how does it relate to the processing of movement within the visual system?

The basis for motion parallax processing must lie in the extraction of information about retinal movement. There has been a large amount of research into how the visual system extracts information about movement and two main models have been proposed as the basis of retinal motion detection. One model assumes that motion is extracted by correlating the response from two units at different points in visual space, where the response from one unit is subject to a time delay (Reichardt, 1961; Barlow and Levick, 1965). The other model, which has recently been formally defined by Marr and Ullman (1981), assumes that the temporal change at individual zero crossings is the basic input for the movement processing system. Whichever model is found to be more appropriate, there is good empirical evidence for the existence of velocity-sensitive mechanisms both physiologically, in the visual system of cats, birds and monkeys and, psychophysically, in the human visual system (Grüsser and Grüsser, 1973; Pantle and Sekuler, 1968; Tolhurst et al., 1973).

The sensitivity functions for depth surfaces specified by motion parallax show that the system is highly sensitive to depth modulation over a limited range of spatial frequencies. This depth sensitivity requires the detection of very small relative displacements over relatively large areas of visual space. The velocity mechanisms underlying the processing of parallax depth must be organised so that such information can easily be extracted. A plausible hypothesis is that the basic mechanism for processing motion parallax information is extended in space and extracts relative velocities within its receptive field. If different units process relative motion over a limited range of different spatial extents (between one and ten degrees), a sensitivity function of the observed shape would be expected. A similar organisation would also seem to be likely in the stereo domain, which shows a similar sensitivity function. In this case, the basic mechanisms would process differences in disparity, rather than velocity, across a range of spatial extents.

In the luminance domain, the sensitivity function also shows a low and high frequency fall in sensitivity. This has been explained in terms of independent channels within the visual system which are tuned to different ranges of spatial frequency. Such a model has proved useful in understanding many aspects of luminance processing. Schumer and Ganz (1979) have suggested that independent channels are also present in the disparity domain. They suggest that mechanisms which pick up disparity differences over areas of the same spatial extent are grouped together at a higher level. This results in a set of phase-independent channels each of which picks up disparity change over a different spatial extent. The experiments reported here, however, failed to find any evidence of phase-independent channels responding to depth change, whether the depth was specifed stereoscopically or by motion parallax. From the present data then, it seems more likely that the observed sensitivity functions arise from a range of phase-specific mechanisms which pick up relative disparity, or relative velocity, over different areas, and these mechanisms are not grouped together in the form of phase-independent channels.

Further evidence for this type of spatial organisation is provided by the demonstration of large successive and simultaneous contrast effects for depth surfaces specified both by parallax information and stereoscopically. Classically, the presence of such effects within a sensory dimension has been attributed to spatial and temporal inhibition between mechanisms within that dimension. In such a model processing is essentially seen as being done point by point, and the output of the processing at any point is then modified by input from neighbouring points in space or time. As argued in chapter 5, however, the existence of large negative depth aftereffects is difficult to explain in terms of the adaptation of individual velocity or disparity detectors. It seems more plausible to argue that these aftereffects arise from the adaptation of mechanisms which respond to relative disparties, or velocities, over space. This places a rather different emphasis on the spatial interactions demonstrated by the presence of simultaneous contrast effects. It could be that these spatial interactions reflect the characteristics of the basic coding mechanisms, rather than a subsequent "distortion". In the case of motion parallax, for example, rather than the velocity at individual points in visual space being the primary coding variable, with these values then being modified by the velocities of neighbouring points, the coding of patterns of velocity over fixed spatial areas could be primary. In this case relative motion might be coded without any explicit coding of individual velocities.

Such a hypothesis would be consistent with both psychophysical and physiological findings. It has been well-established psychophysically that perceived movement depends not just on the movement of the element under consideration but also on the movement of surrounding elements. This is of course the phenomenon of induced movement first noted by Duncker (1929) and studied more recently by several authors (Loomis and Nakayama, 1973; Tynan and Sekuler, 1975; see chapter 6). Recent physiological work has provided evidence that units in the visual system of pigeons and monkeys respond best to the relative movement between adjacent retinal areas and similar units in the human visual system may underly the induced movement effects (Frost, 1978; Frost et al., 1981; Allman et al., 1982).

Taken overall, the data suggest that a plausible hypothesis for the nature of motion parallax processing is that it is based on units with extended receptive fields which detect relative motion. This also seems to be a likely organisation for the processing of disparity. In particular, the simultaneous contrast effect indicate that the nature of the spatial interactions involved can be inhibitory. This suggests that the receptive fields of the depth processing mechanisms have excitatory and inhibitory subregions. For example, for motion parallax, the response of the unit would be enhanced by movement in a specific direction in the excitatory region and reduced by movement in the same direction in the inhibitory region. The inhibitory region may surround the excitatory centre. Alternatively, the units may show a double opponency where the centre region is excited by movement in one direction and inhibited by movement in the other, while the surrounding region is excited by movement in the opposite direction and inhibited by movement in the initial direction (Figure 9.1a). The latter organisation, which is similar to that thought to operate in the colour system, has been suggested by Nakayama and Tyler (1979) on the basis of their data on the visual system's sensitivity to differential movement.

Although motion parallax must be based on the extraction of relative motion, that information, by itself, is insufficient to specify three-dimensional structure. Within any local area, a given pattern of relative motion does not unambiguously specify the depth structure at that point, as shown for example, by the ambiguity inherent in the Kinetic Depth Effect. For motion parallax, it has traditionally been assumed that this ambiguity is resolved by taking vestibular or kinaesthetic information about head and eye movements into account. However, the experiments in this thesis have shown that active movement of the observer is not necessary to provide unambiguous depth information, provided that the movement of the object carrying the relative motion can be accurately determined. In the passive parallax situation used here, where the perceived depth was unambiguous, the relative movement was linked to the movement of the oscilloscope across the line of sight and the direction of translation of the scope could easily be perceived in the dimly-lit room. This finding demonstrates that the disambiguating information can come from a purely visual source and does not require active observer movement. The disambiguating information might also be purely visual in the active parallax situation even though vestibular information is also available. The visual information necessary to disambiguate the relative motion would need to come from a relatively large area of the visual field. It must specify whether the relative motion is due to the translation of the observer or of the object, as well as the direction of the translation.

A crude mechanism for this task would be one which responded to the relative motion of the foveal area of interest with respect to the rest of the visual field. The relative motion detectors found physiologically, which have receptive fields subtending twenty or more degrees of visual angle, would seem to be ideally suited to this task (Frost, 1978; Frost et al., 1981; Allman et al., 1982). It seems likely, therefore, that these units would be more useful for extracting the essential disambiguating information needed for depth interpretation, rather than the fine grain detailed information about local depth structure.

The depth effects which were observed for parallax depth surfaces were closely related to those obtained in studies of differential motion rather than depth surfaces (Nakayama and Tyler, 1981). As mentioned above, Nakayama and Tyler suggest that relative velocity mechanisms with a centre-surround double opponency organisation would explain their data on the detection of differential movement. Since the patterns of relative movement used in their displays were very similar to those used here to investigate parallax depth, it is likely that they both stimulated the same mechanisms. The extraction of motion parallax, of course, requires further processing so that the relative motion information can be unambiguously interpreted in terms of relative depth. It could be that this disambiguating information is added at a later stage, after the differential movement has been processed by mechanisms with the suggested spatial organisation. In this case, the basic spatial organisation would be at the level of relative movement processing rather than depth processing. On the other hand, the parallax depth effects are also similar to those observed in the stereoscopic domain. As argued above, it seems likely that disparity processing mechanisms are organised with an excitatory/inhibitory receptive field structure. In this case, the contrast effects arise because of the receptive field organisation at the level of depth interpretation itself. Hence, by analogy, motion parallax processing mechanisms might also have a receptive field structure subsequent to the interpretation of motion information as depth. In either case, the negative depth aftereffects which were found to occur for parallax depth, must arise at a level at or beyond that where the disambiguating information has been incorporated and this implies a spatial organisation at this level. Perhaps, therefore, the basic type of local mechanism is more likely to be coded in terms of depth rather than motion, although the two are clearly closely related. If this were the case then the effects observed for differential motion patterns might arise from mechanisms primarily designed to extract depth information but which also respond, non-optimally, to differential motion.

It seems, therefore, that a likely basis for motion parallax processing is a population of relative motion detectors which pick up relative movement over different spatial areas. Relative motion detectors with very large receptive fields would provide disambiguating information which would allow the local depth structure, detected by more finely tuned mechanisms, to be determined unambiguously. The larger detectors would only have to provide qualitative information about direction of motion, while the finer mechanisms would specify the local depth structure in accurate detail.

A priori, it might seem likely that these basic parallax mechanisms might have a simple symmetric centre-surround organisation

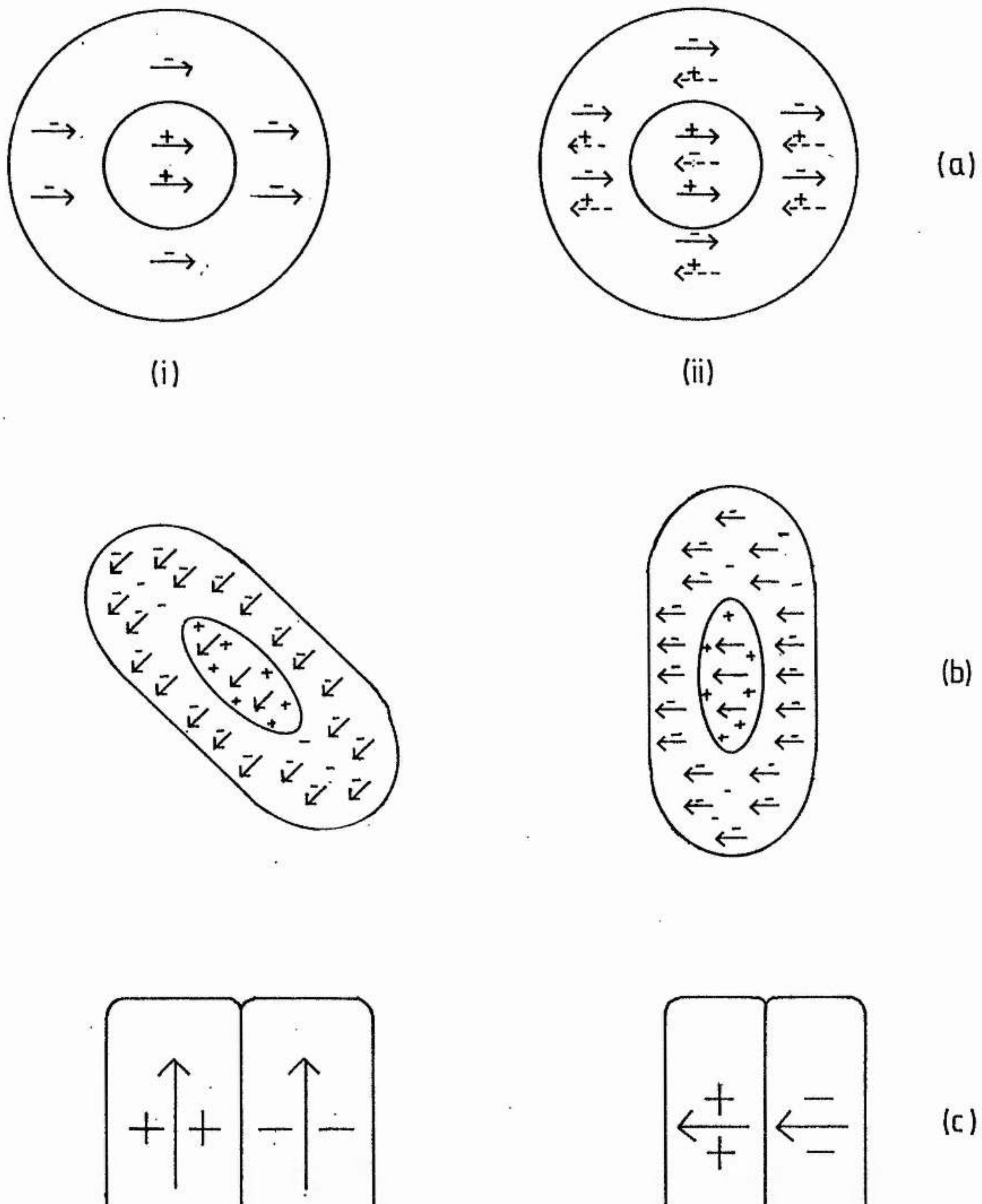


Figure 9.1.
Receptive field models of basic mechanisms which could process relative motion and provide the basis for processing depth from motion parallax.
(a) A simple symmetrical centre-surround organisation. In (i) the unit would be excited by movement, in its preferred direction, in the centre of the field and inhibited by movement in that direction in the surround. In (ii) the unit shows double-opponency with movement in opposite directions excitin centre and surround.
(b) Oriented receptive field organisation; the axis of elongation is always orthogonal to the units preferred direction of motion. The optimal spatial frequency for the unit would be lower in the orthogonal direction.
(c) The two types of mechanism described by Clocksin (see chapter 2) can be represented in recptive field form as shown. To explain the anisotro (ii) would have to be narrower than (i).

(Figure 9.1a) where the response is excited by movement in the preferred direction within the excitatory centre and inhibited by movement in that direction in the surround. However, there is psychophysical evidence for anisotropies in the processing of both parallax and stereoscopic information (chapter 7). These findings suggest that an asymmetric organisation might be more likely. A simple asymmetry in the receptive field organisation of depth detecting mechanisms would, in fact, explain the observed patterns of anisotropies very simply. Suppose the receptive field was organised, as shown in Figure 9.1b, with the axis of elongation of the receptive field always orthogonal to the preferred direction of motion. Then for this particular mechanism, the width of the receptive field in a direction orthogonal to the direction of motion is greater than the width in a direction parallel to the direction of motion. Hence, the spatial frequency of differential motion (or depth grating) which would optimally stimulate the detector would be lower in the former case. That is, the optimal spatial frequency response of such a detector, which extracts the spatial differentials of velocity across its receptive field, would be lower when the spatial differential was computed orthogonally to the preferred direction than when it was computed parallel. The anisotropy would, therefore, not be linked to any horizontal/vertical differences per se, since receptive fields could be oriented at any angle. The important point is that the field would always be elongated in a direction orthogonal to the direction selectivity of the unit.

An alternative, but related, explanation is that detectors do not have a centre-surround organisation but only have inhibitory flanks on one or both sides. In this case, to explain the anisotropy, the predominant size of the receptive fields would have to be larger when the preferred direction of movement was orthogonal to the axis of the receptive field and units which pick up change in the same direction, would have narrower receptive fields. It is interesting that computational models of the processing of optic flow point to the necessity of computing spatial velocity differentials in two orthogonal directions. Oriented receptive fields of the type just described, in which the direction sensitivity is either orthogonal or parallel to the axis of the receptive field, would be able to perform the appopriate computation. Such units would in fact be very similar to the hypothetical mechanisms suggested by Clocksin's computational model which was described in chapter 2 (see Figure 9.1c).

Since the parallax and stereoscopic depth systems have been shown to share many empirical characteristics, it has been suggested throughout that mechanisms within the stereoscopic system might have a receptive field organisation similar to that outlined for parallax. The anisotropies which were found for stereoscopic surfaces suggest that mechanisms which extract relative disparity have larger inhibitory regions for extracting change in disparity in a direction orthogonal to the disparity itself (which is always horizontal), than for extracting change in disparity along the horizontal. The models illustrated in Figure 9.1 could therefore apply to disparity processing as well as the processing of movement.

The spatial organisation that has been proposed as a basis for the processing of parallax depth, computes the shape of three-dimensional surfaces in terms of the slope over local areas of the surface. That is, the parallax depth system seems to be essentially concerned with the three-dimensional form of a specific area, rather than with the absolute depths or distances of individual points. Recent theories of stereoscopic vision have concentrated on explaining how the visual system can compute the disparities of different points of the image to provide a "depth map" of the image. They have tended to ignore the problem of how the depth structure or form of a three-dimensional surface is processed. It is of course possible that the computation of relative disparity over space follows the processing of the disparities of individual points. However, it could also be the case that the processing of relative disparity is the primary coding variable of the stereoscopic process. That is, the disparity of individual points in the visual field may not be explicitly coded in itself. The empirical data collected here, show that the spatial arrangement of depth surfaces is important for stereoscopic vision and has implications for the nature of the underlying processes. It seems that present theories of the stereoscopic process are at best incomplete, since they do not adequately consider the extraction of three-dimensional form, and at worst misguided, if stereoscopic information is based on the patterns of disparity over local areas, rather than the disparities of individual points.

One final question is whether motion parallax and stereopsis are essentially independent depth processing mechanisms or whether they come together at some level of processing. Since the two systems use very different sources of information, relative velocity in the one case and disparity in the other, they must be independent in their initial processing stages. However, even at this level the types of mechanisms which extract the relative motion or disparity information seem to share a similar spatial organisation, as discussed above.

Moreover, there is evidence that depth information from the two systems interacts at two different levels. Firstly, stereoscopic information appears to influence the processing of parallax information at an early stage, and determines whether the relative motion is interpreted as depth or as object movement. The interaction at this level shows no quantitative combination of depth from the two sources. It was also found, however, that information from both depth sources could interact quantitatively in some conditions. For example, depth aftereffects could be nulled with depth specified by the other depth cue. It seems possible, therefore, that the two systems come together, perhaps in the form of a general depth mechanism, at a higher level.

In summary, the work in this thesis has provided some initial empirical data on the processing of motion parallax information by the human visual system. Motion parallax has been shown to be an effective source of depth information and to share similarities with stereopsis. The possibilty of extensively studying a depth cue other than stereopsis, has provided insight into the general nature of depth processing as well as the mechanisms specific to motion parallax. In particular, the study of motion parallax has highlighted the importance of processing depth structure over space and suggested that depth processing in general might be primarily concerned with extracting information about the local structure of depth surfaces. The investigation of how we perceive depth surfaces would seem to provide the most fruitful area for future empirical and theoretical work in the area of depth perception.

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